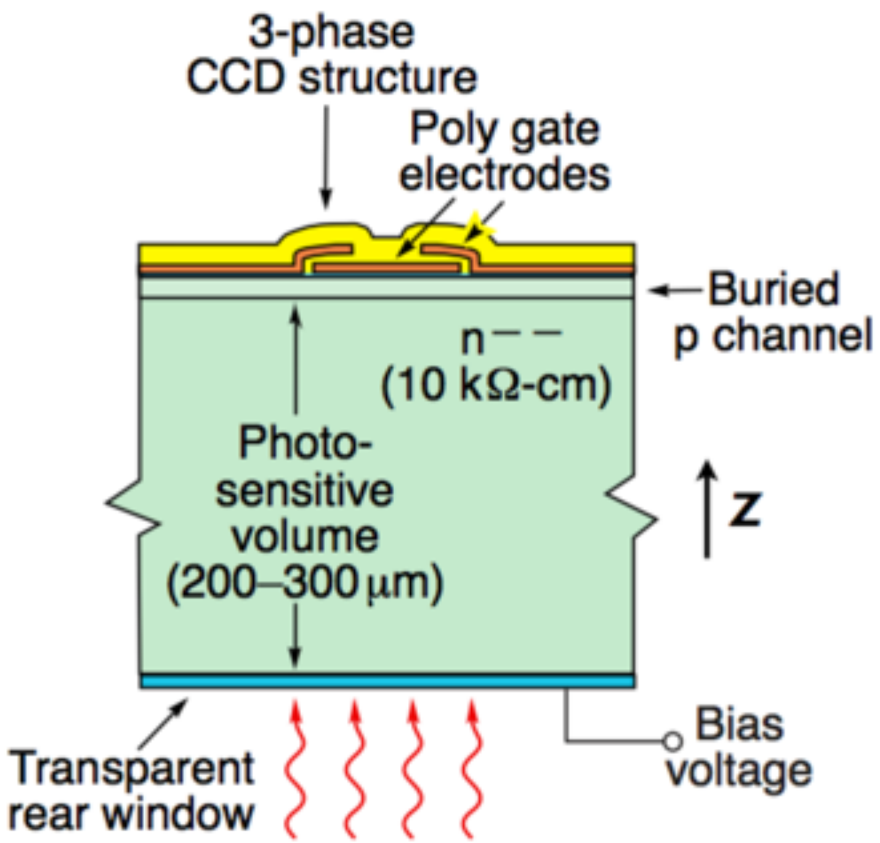
Dark Matter in CCDs, current status and plans

Juan Estrada - Fermilab

For the DAMIC Collaboration*

*Fermilab, U Chicago, U Zurich, Snolab, U Michigan, UNAM, FIUNA, CAB, UFRJ, U Paris VI & VII

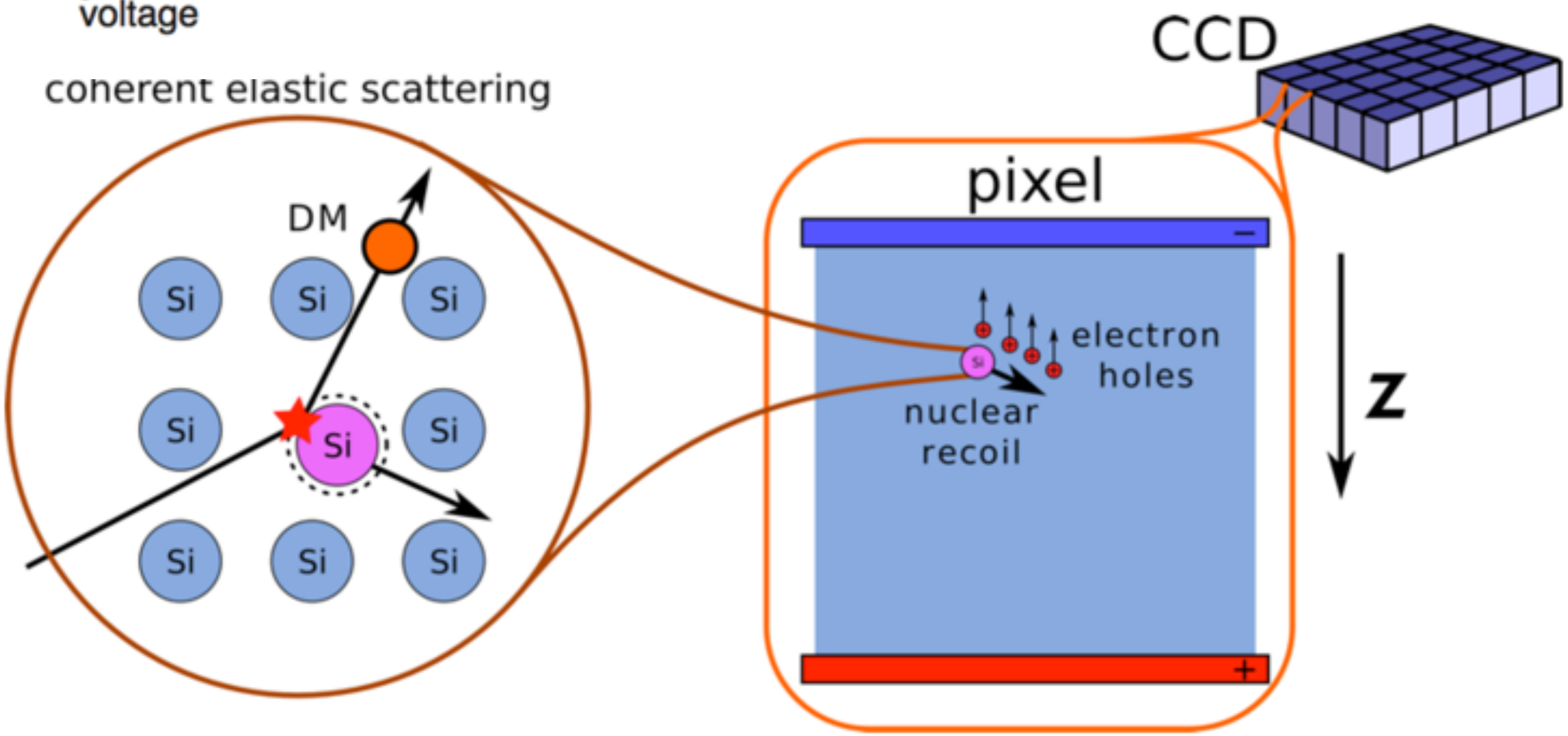
The DAMIC sensors



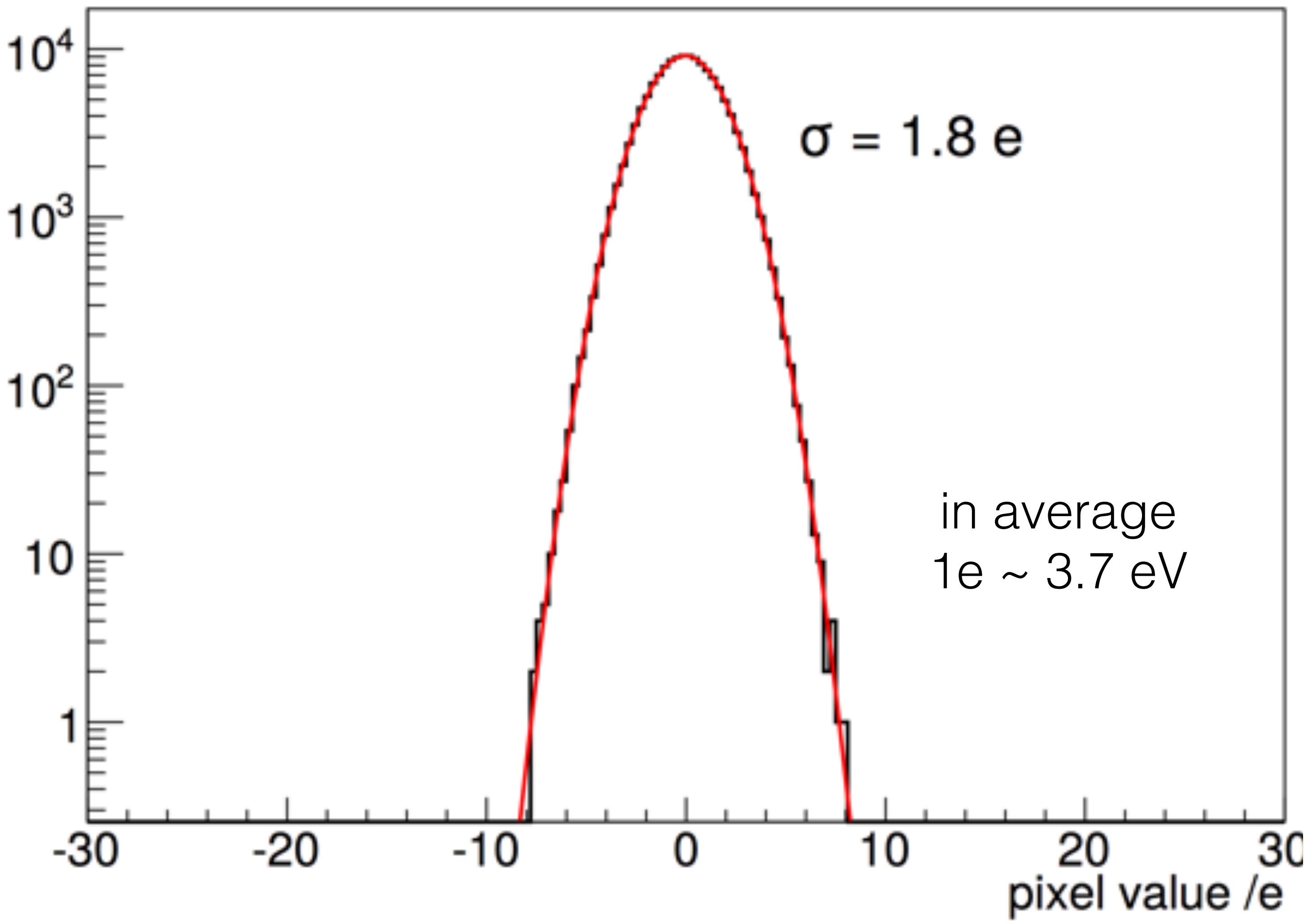
Thick fully-depleted CCD detectors developed at LBNL (S.Holland et al) are the sensors that make this experiment possible.

Steve and his colleagues developed a way to fabricate CCDs in very high resistivity silicon, and get them fully depleted with a substrate voltage applied on the back of the detector.

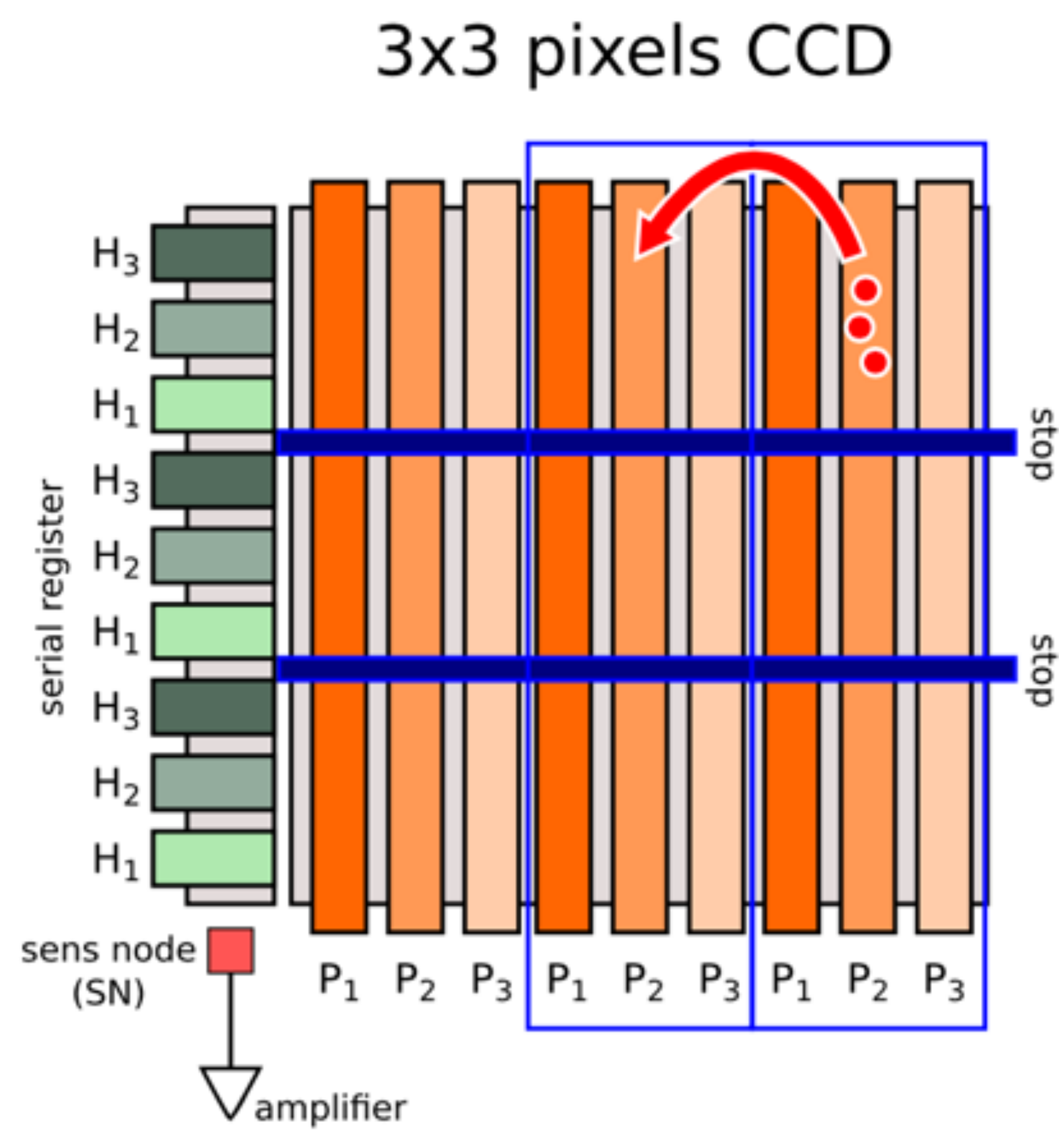
For astronomy (near-IR) the LBNL detectors are up to 250um. To get more mass we are using 675 um thick detectors.



The DAMIC sensors



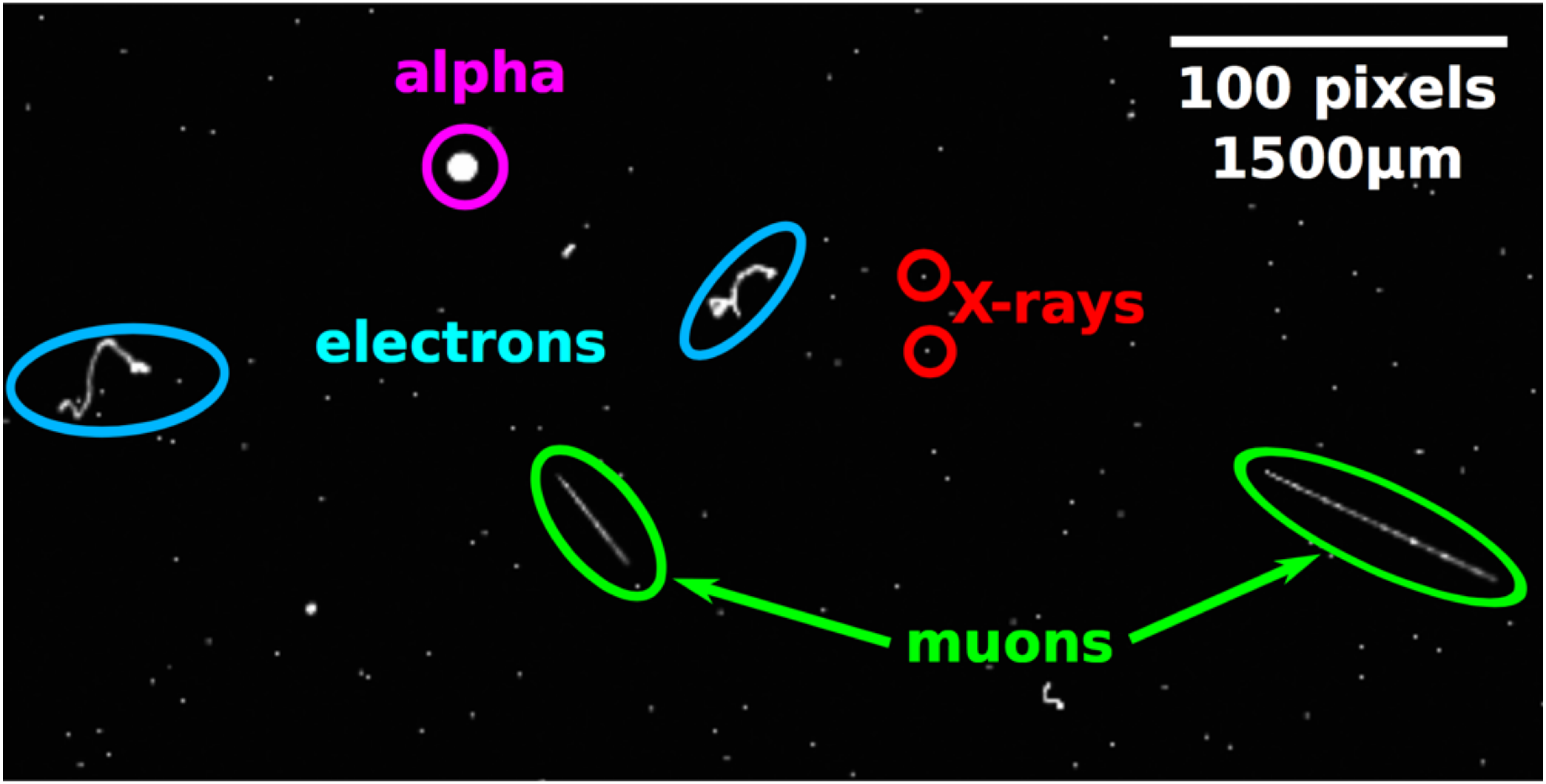
Charge-Couples Devices (CCDs) are extremely low noise, the readout is determined by the capacitance of the output node, and not of the large detector.



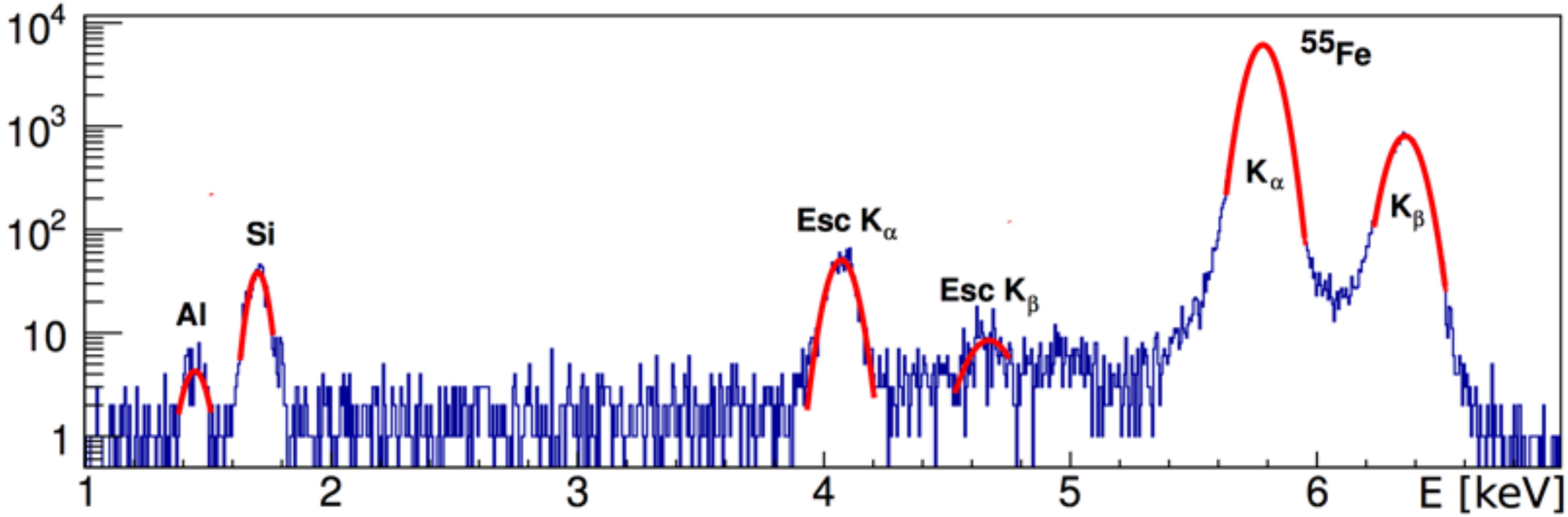
Charge distribution measurement for pixels without signal (no exposure).

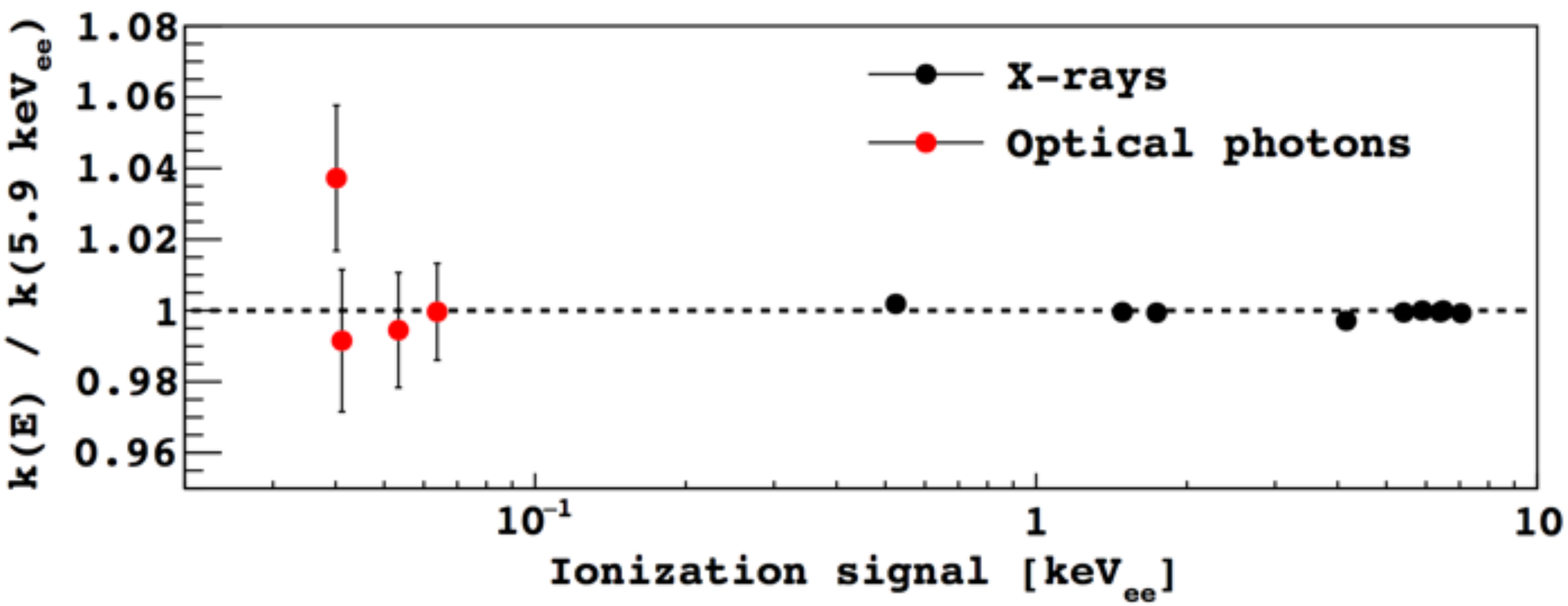
On-chip (analog) binning is also possible to increase signal to noise, more on this later.

Particle ID in CCDs



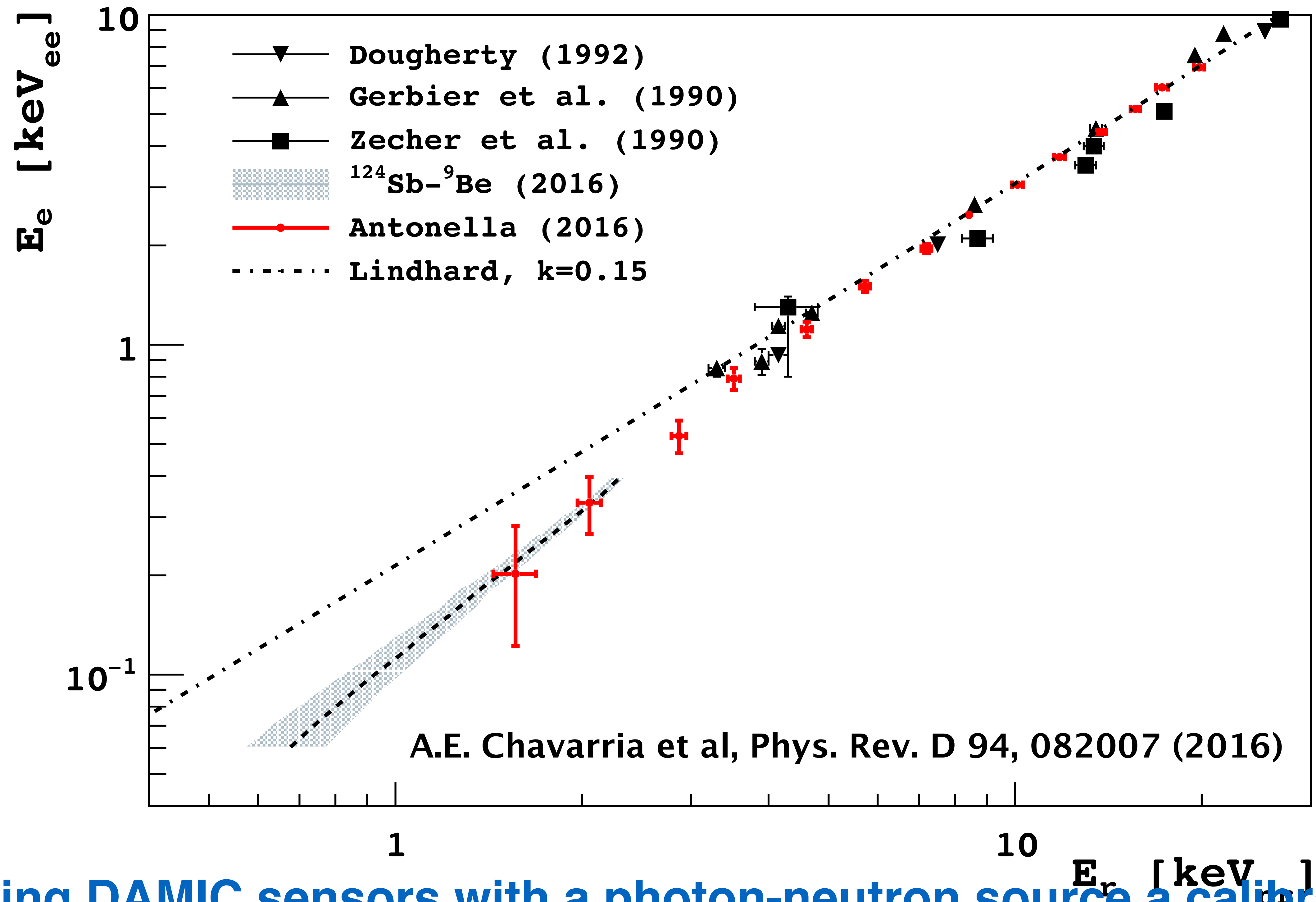
electron recoils calibration





studies with X-rays and low light levels (not shown here) demonstrate very nice linearity response of the sensors.

calibration to low energy nuclear recoils

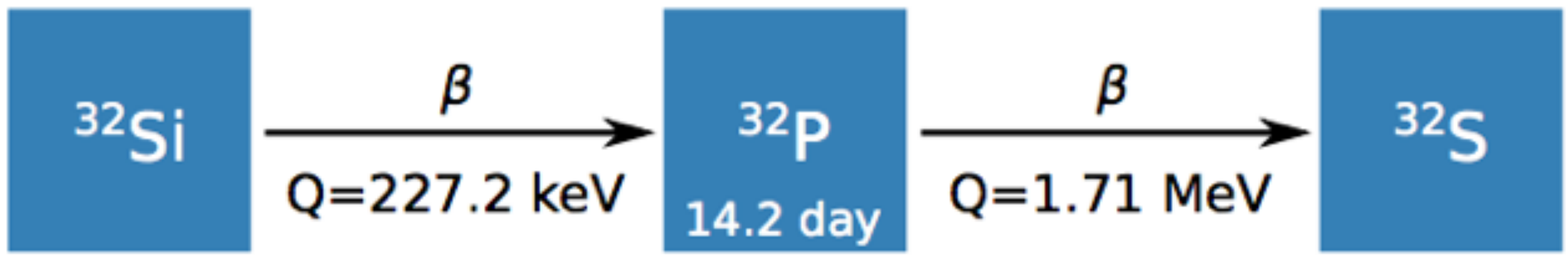


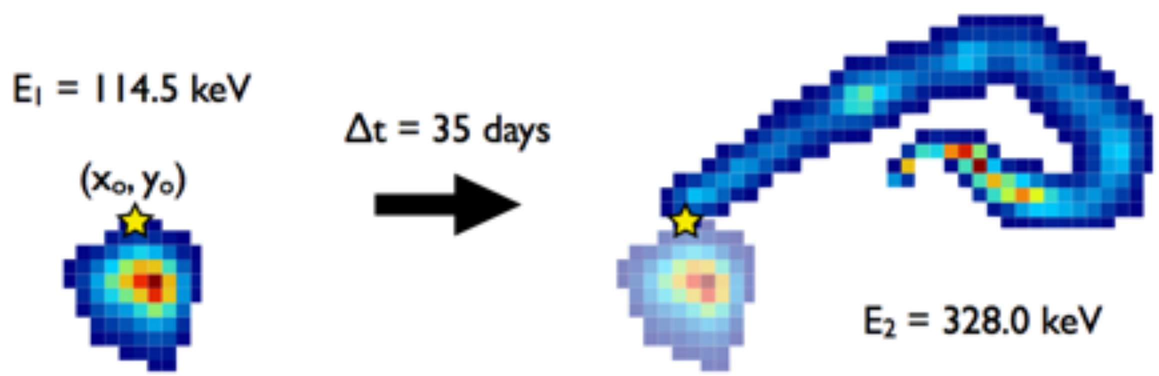
using DAMIC sensors with a photon-neutron source a calibration was produced to 0.7 keVr (previous data to 4 keVr). With a neutron scattering experiment the two data sets were joined.

background in DAMIC CCDs

JINST 10 (2015) P08014

The precise position reconstruction in the CCD allows the study of spatial coincidences to measure and veto ^{32}Si events in the CCD

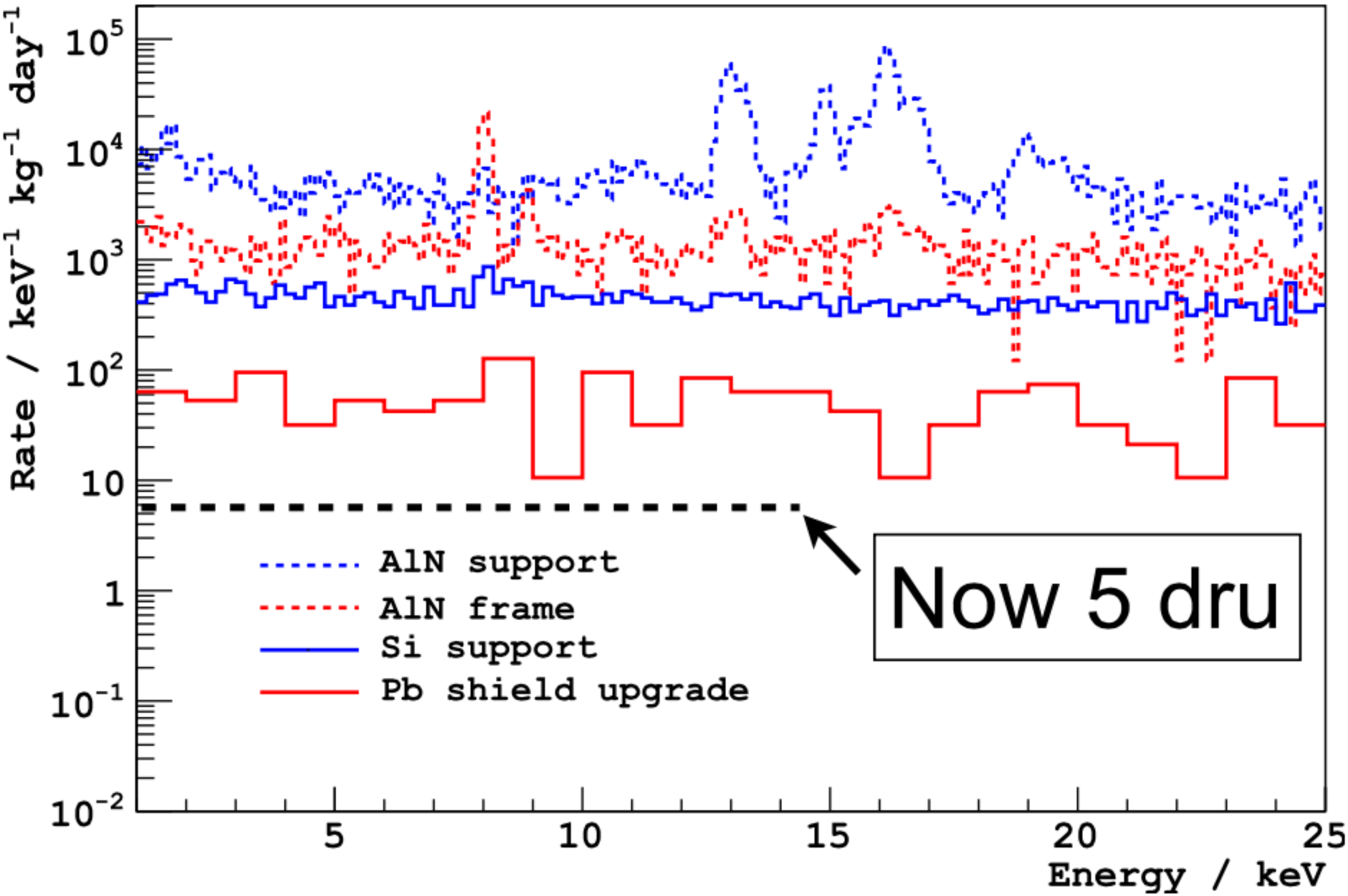




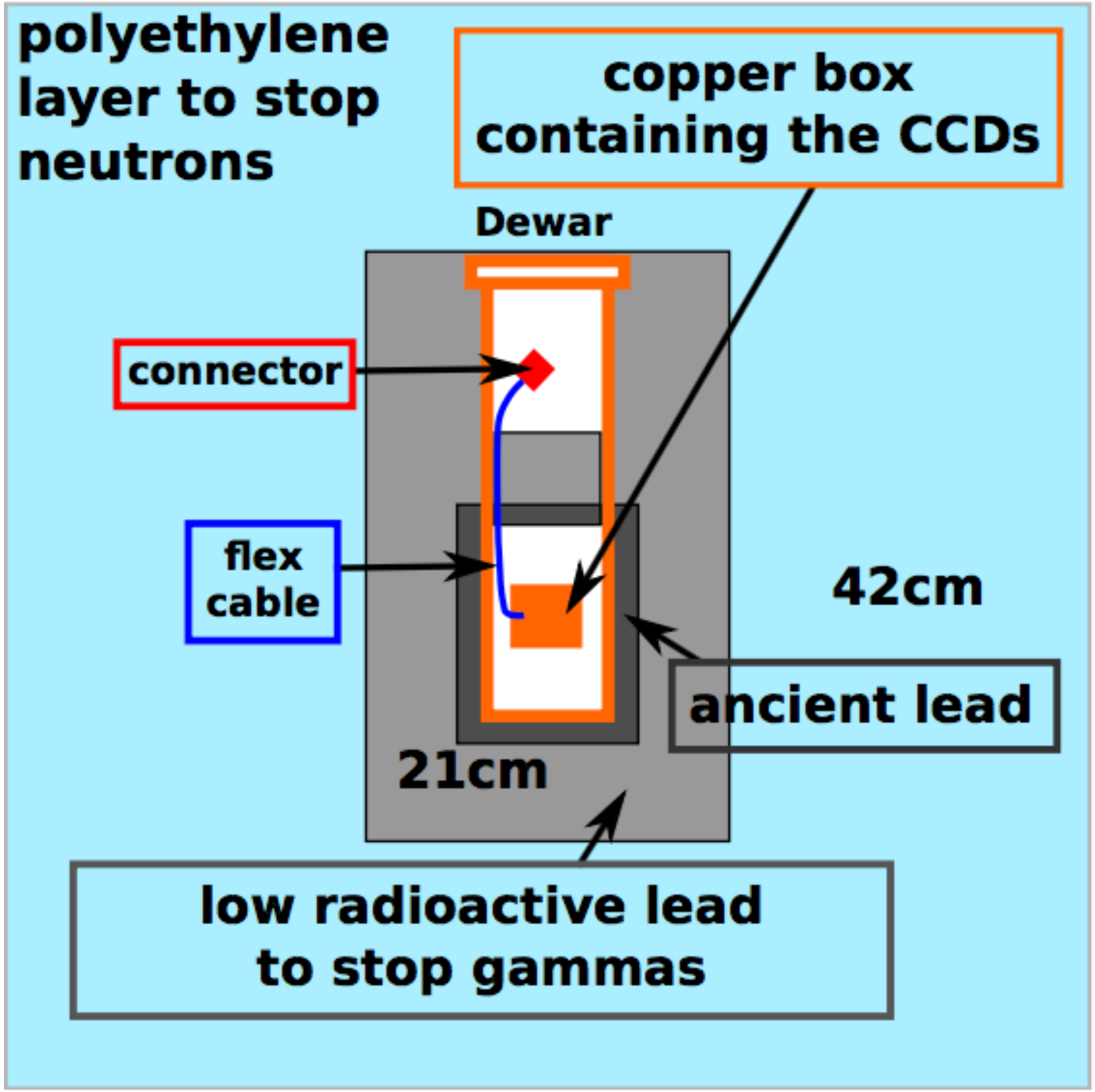
This will be the limiting background in next generation silicon detectors for DM. DAMIC will be able to veto these background.

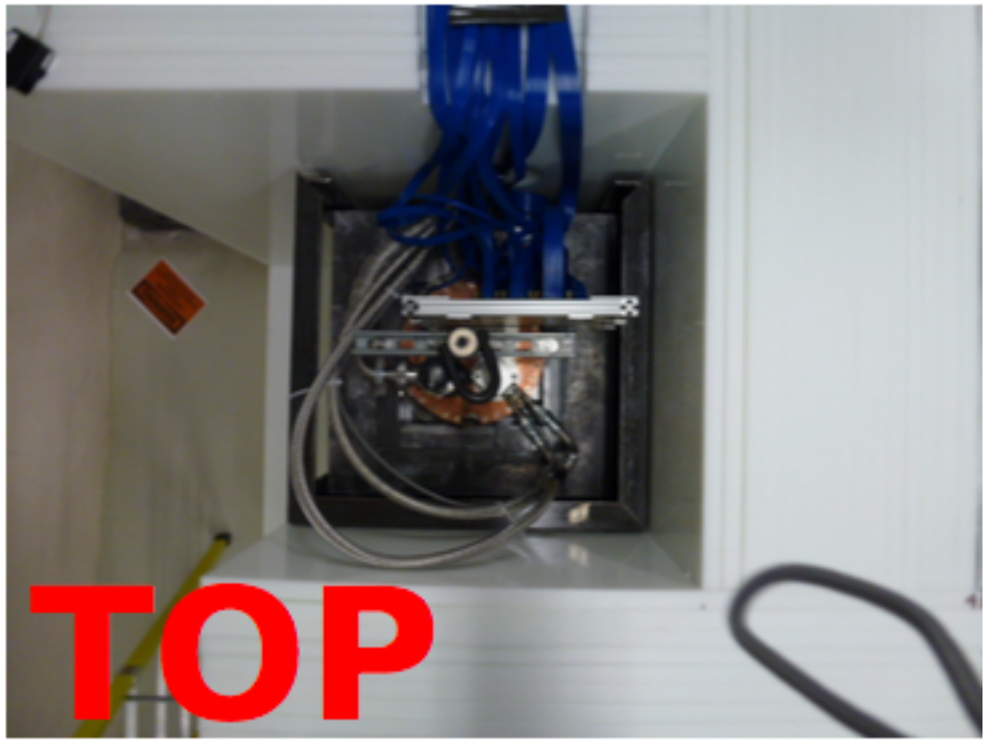
Analysis method	Isotope(s)	Tracer for	Bulk rate kg^{-1} d^{-1}	Surface rate cm^{-2} d^{-1}
α spectroscopy	^{210}Po	^{210}Pb	<37	0.011 ± 0.004, 0.078 ± 0.010
	^{234}U + ^{230}Th + ^{226}Ra	^{238}U	<5 (4 ppt)	–
	^{224}Ra – ^{220}Ra – ^{216}Po	^{232}Th	<15 (43 ppt)	–
β spatial coincidence	^{32}Si – ^{32}P	^{32}Si	80^{+110}_{-65}	–
	^{210}Pb – ^{210}Bi	^{210}Pb	<33	–

DAMIC at SNOLAB 2012-2015 reduced background 3 orders of magnitude.

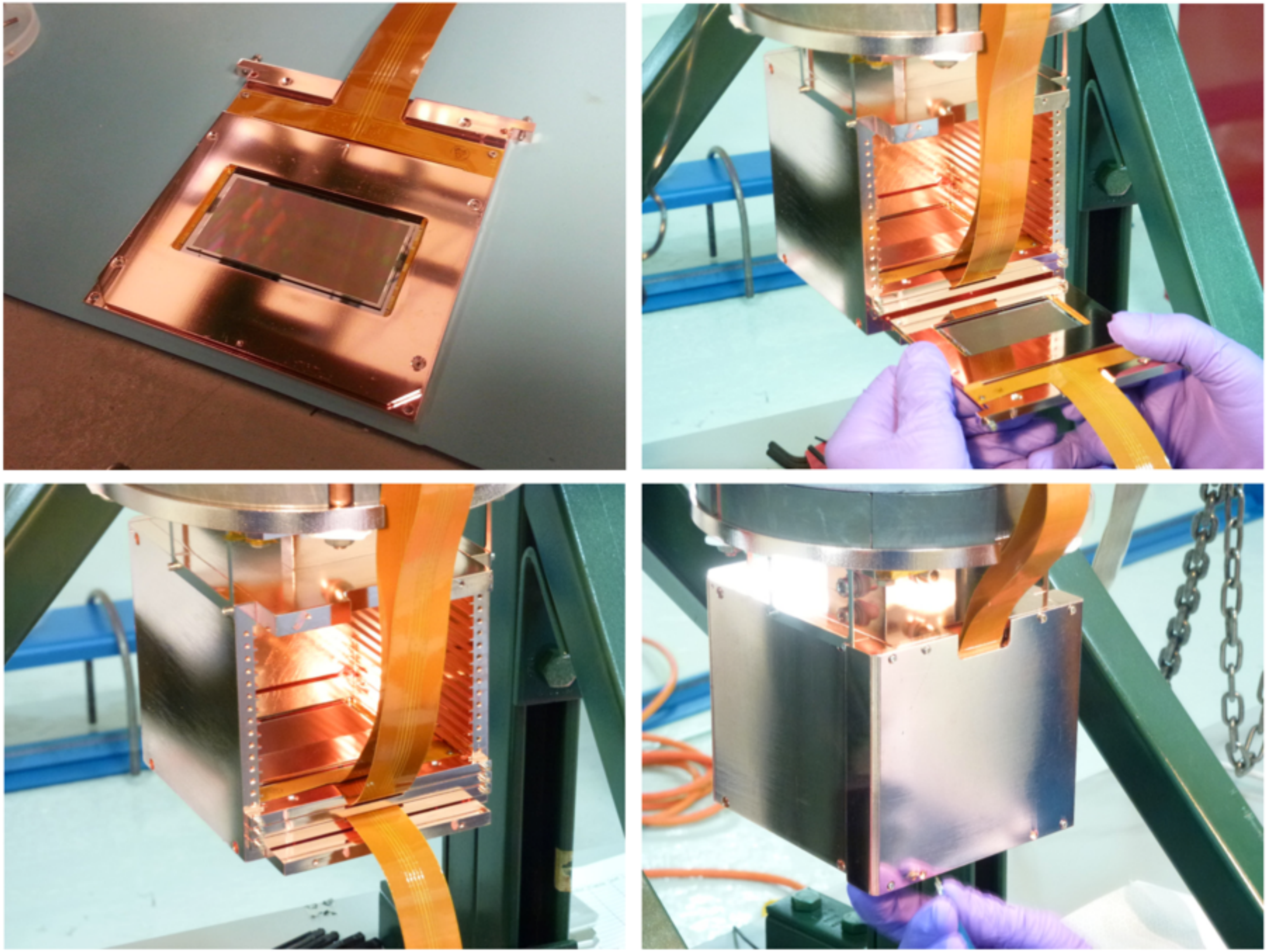


DAMIC detector design





DAMIC detector design



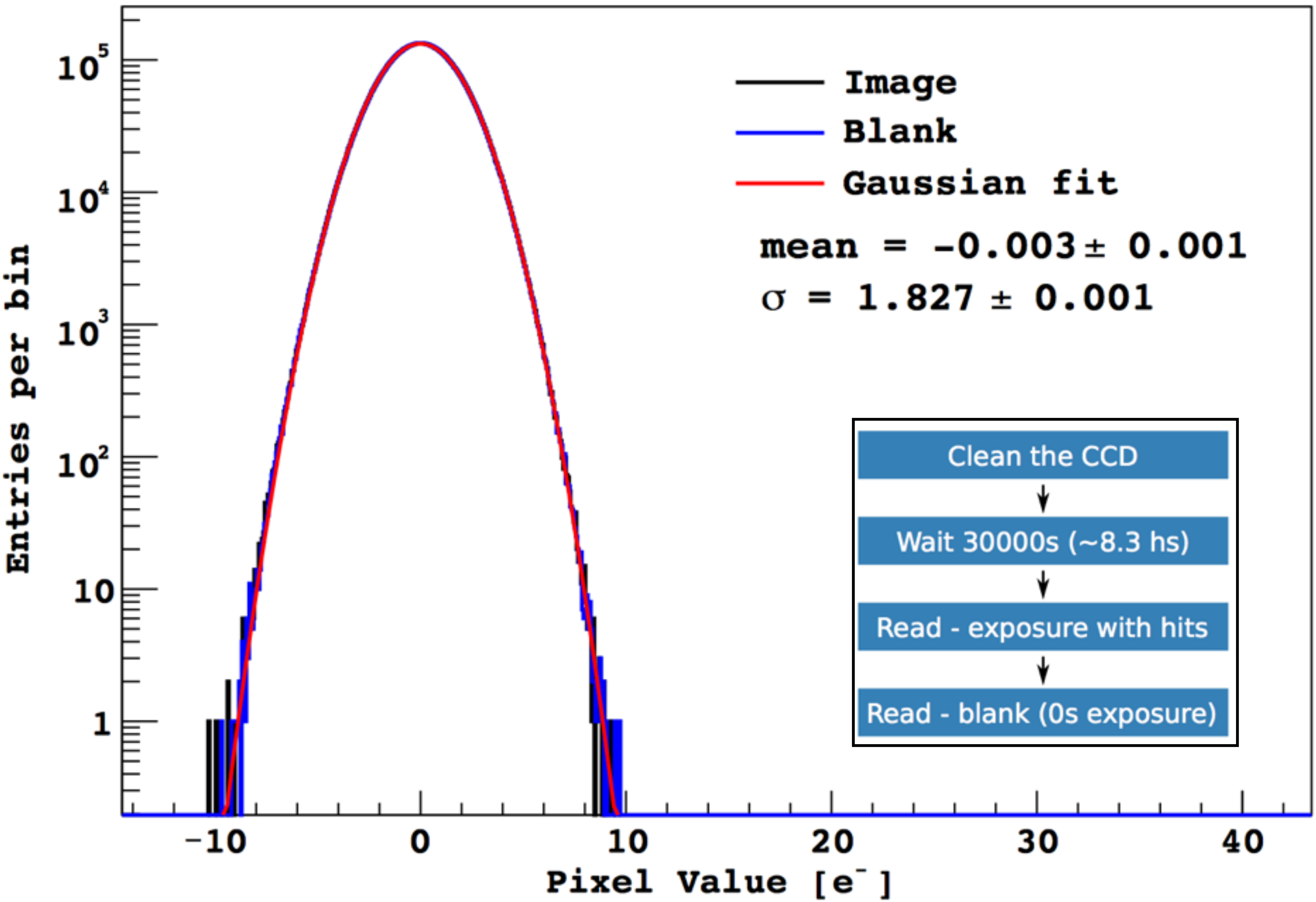
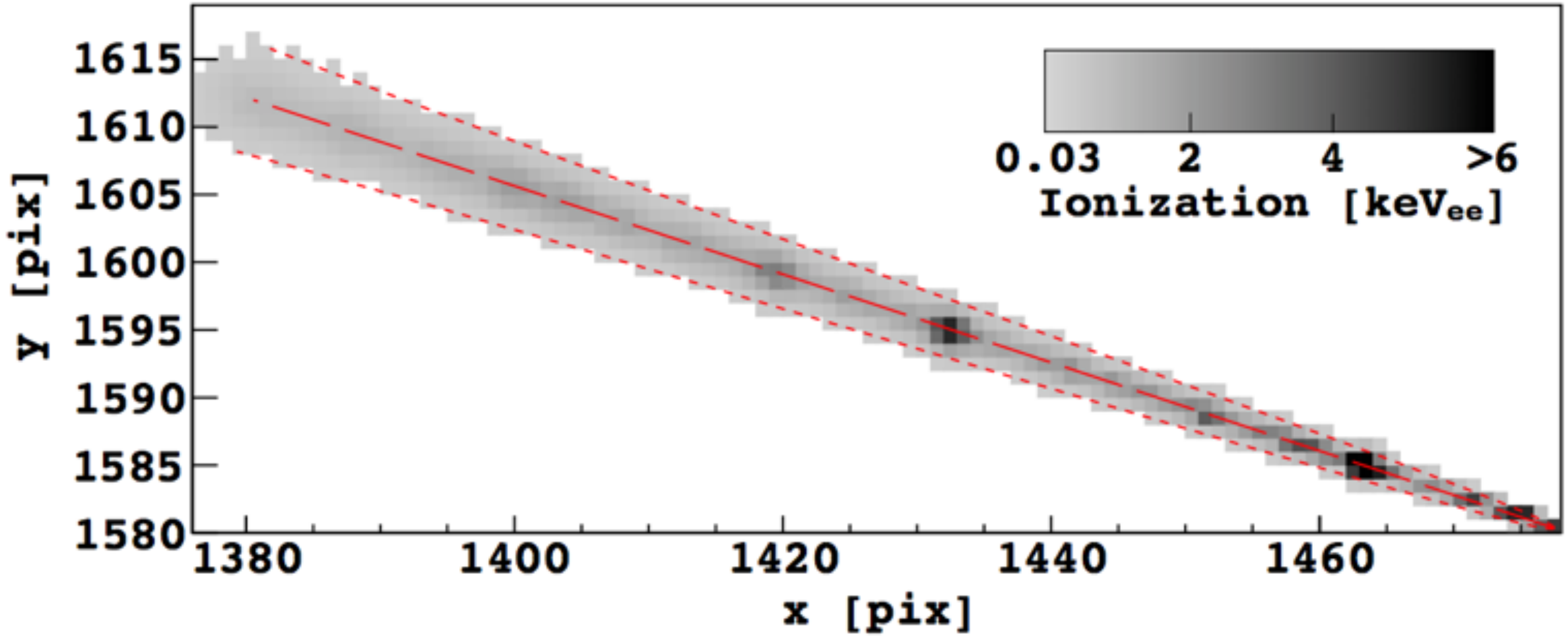
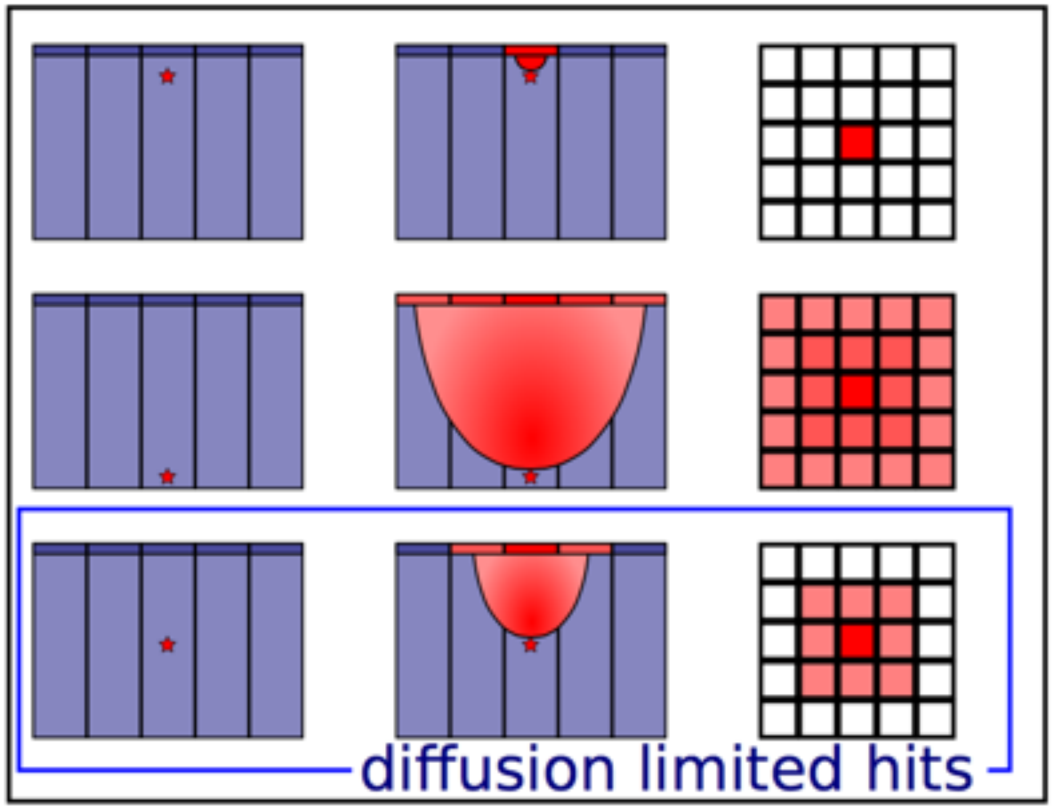


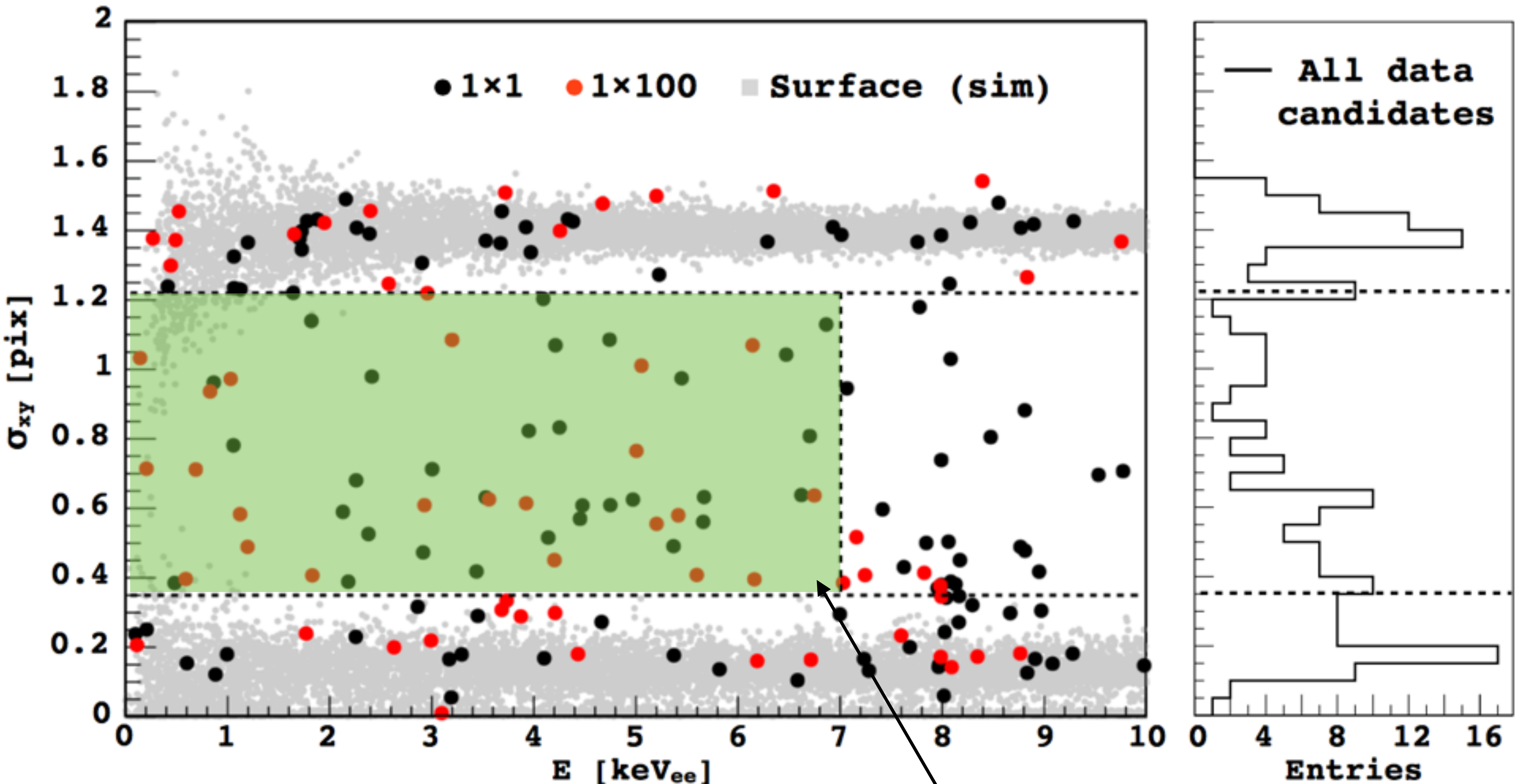
Image
Blank
Gaussian fit
mean = -0.003 ± 0.001
σ = 1.827 ± 0.001
Clean the CCD
Wait 30000s (~8.3 hs)
Read - exposure with hits
Read - blank (0s exposure)
Entries per bin
Pixel Value [e⁻]

MIP track allows measurement of diffusion in silicon





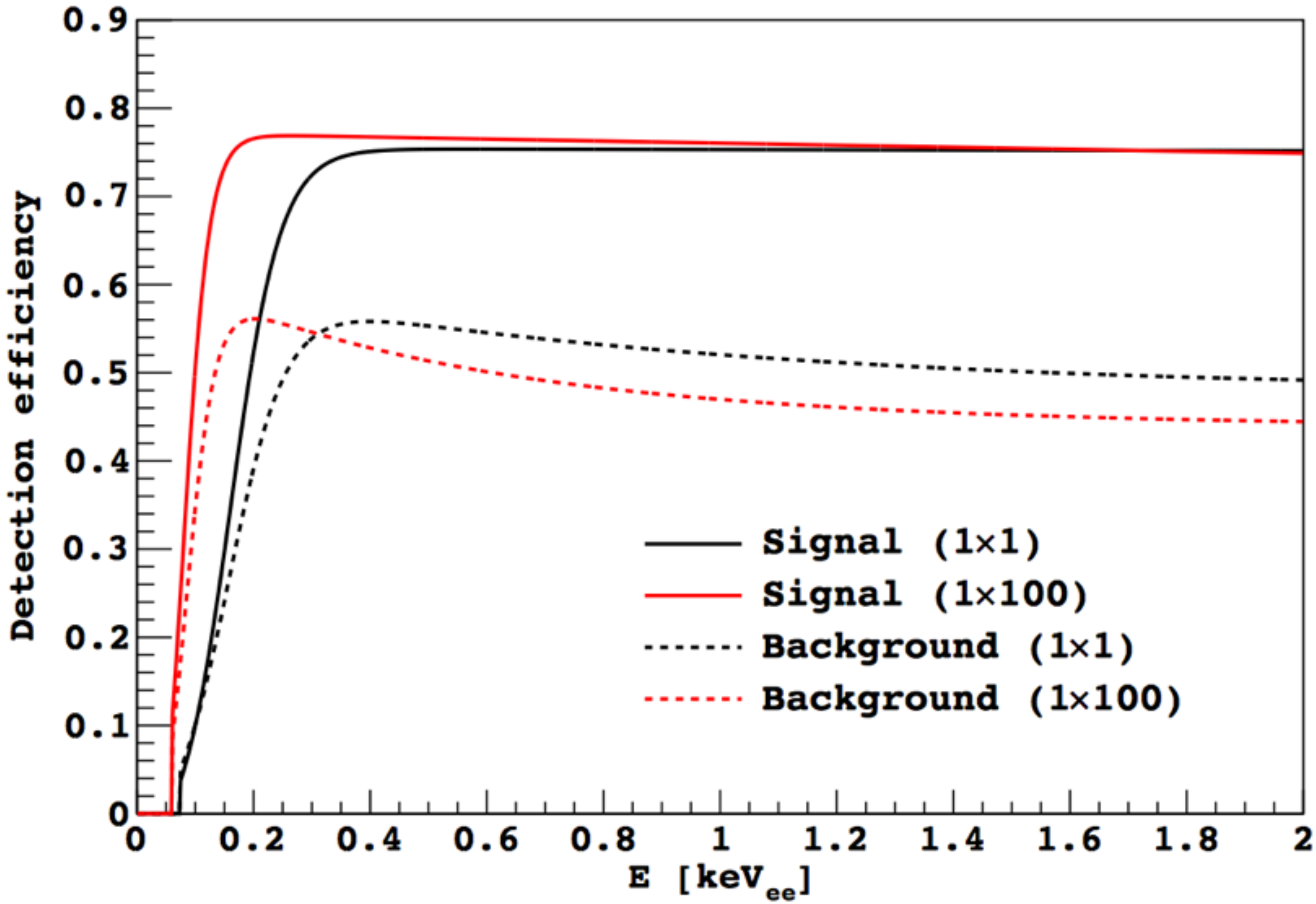
DAMIC data at SNOLAB



signal region

Phys. Rev. D 94, 082006 (2016)

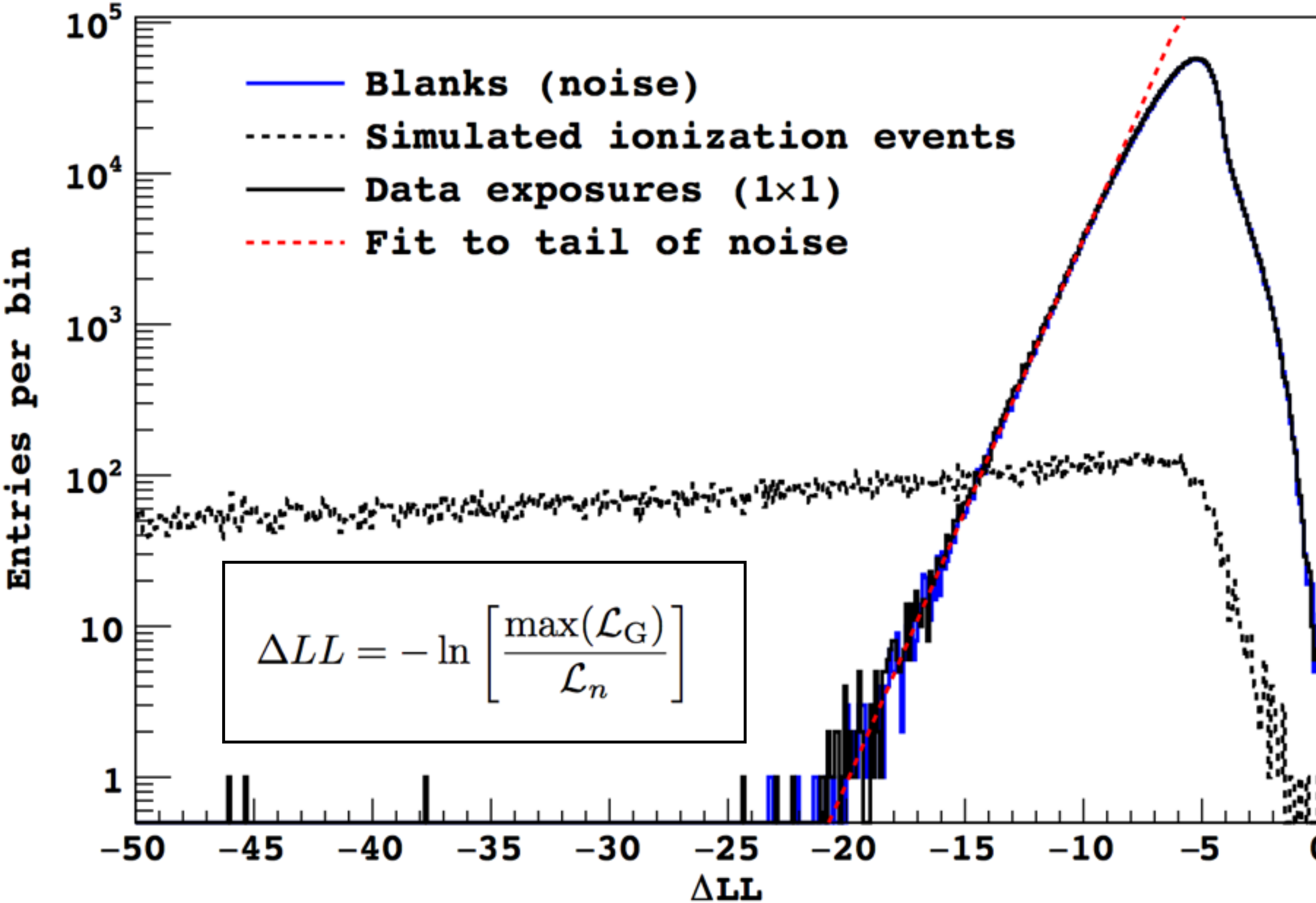
DAMIC data: efficiency



validates using ^{57}Co data.

Phys. Rev. D 94, 082006 (2016)

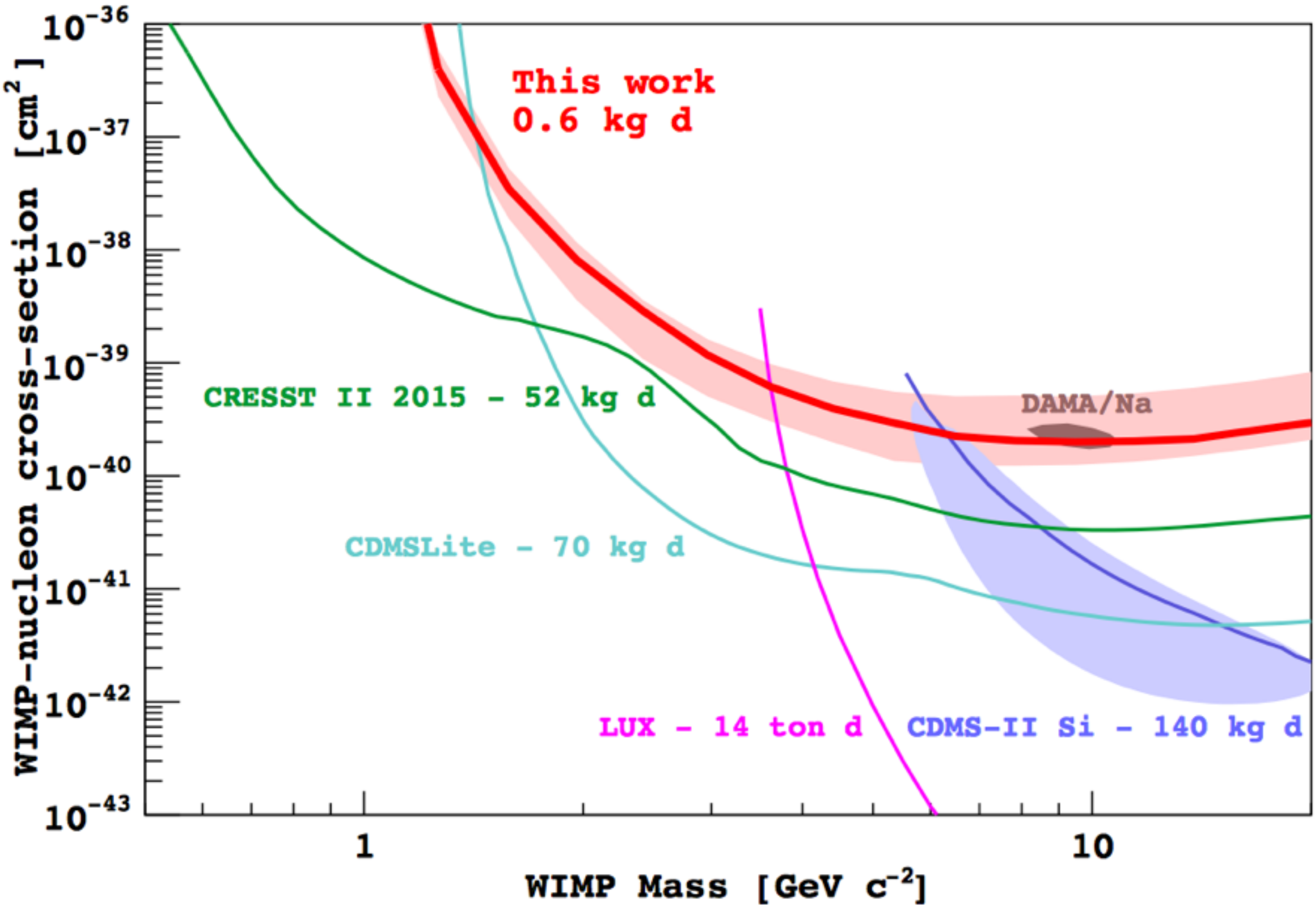
noise/signal likelihood ratio based on diffusion model



Phys. Rev. D 94, 082006 (2016)

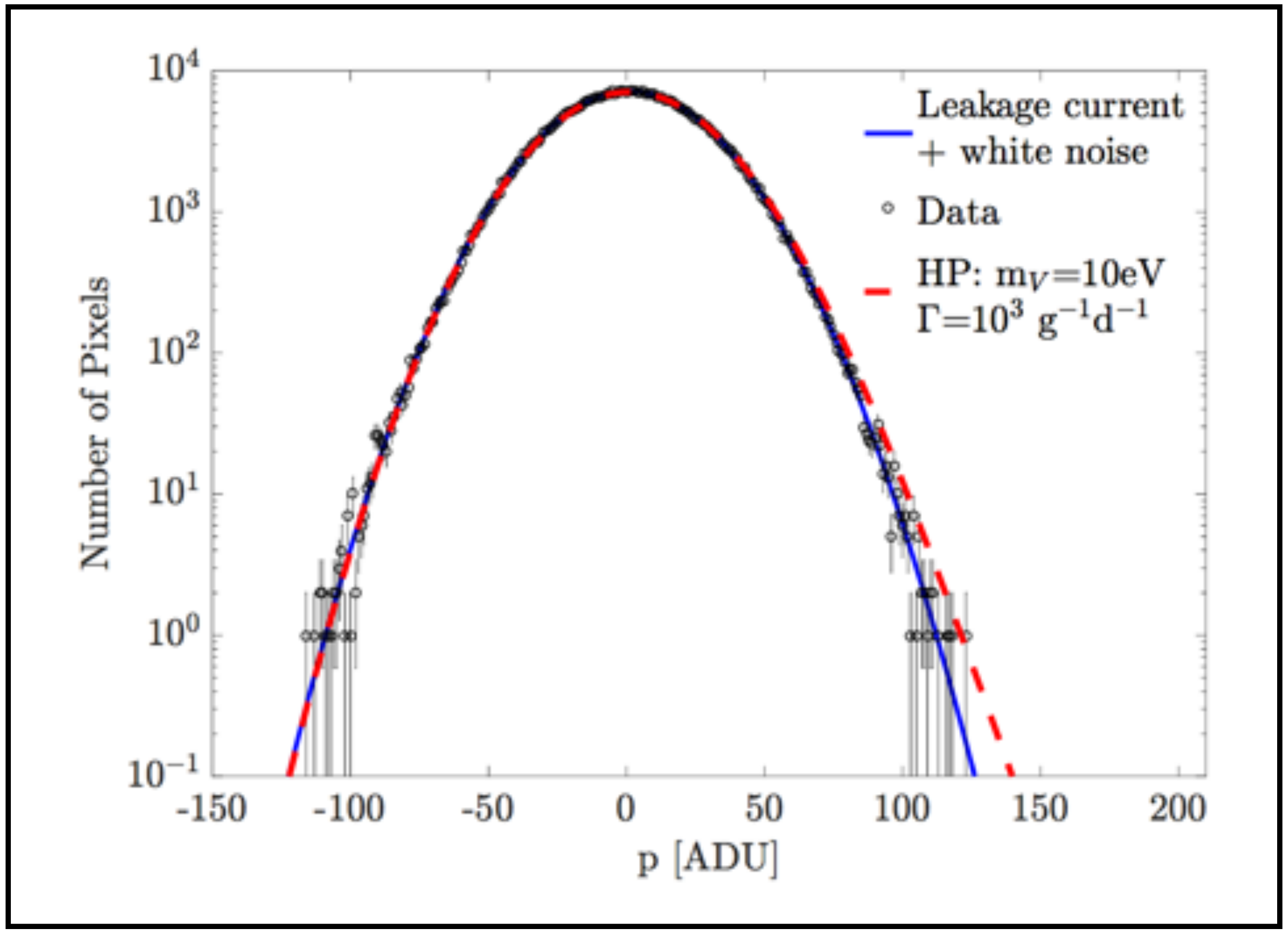
$15 \pm 3\,\mathrm{keV}_{ee}^{-1}\,\mathrm{kg}^{-1}\,\mathrm{d}^{-1}$

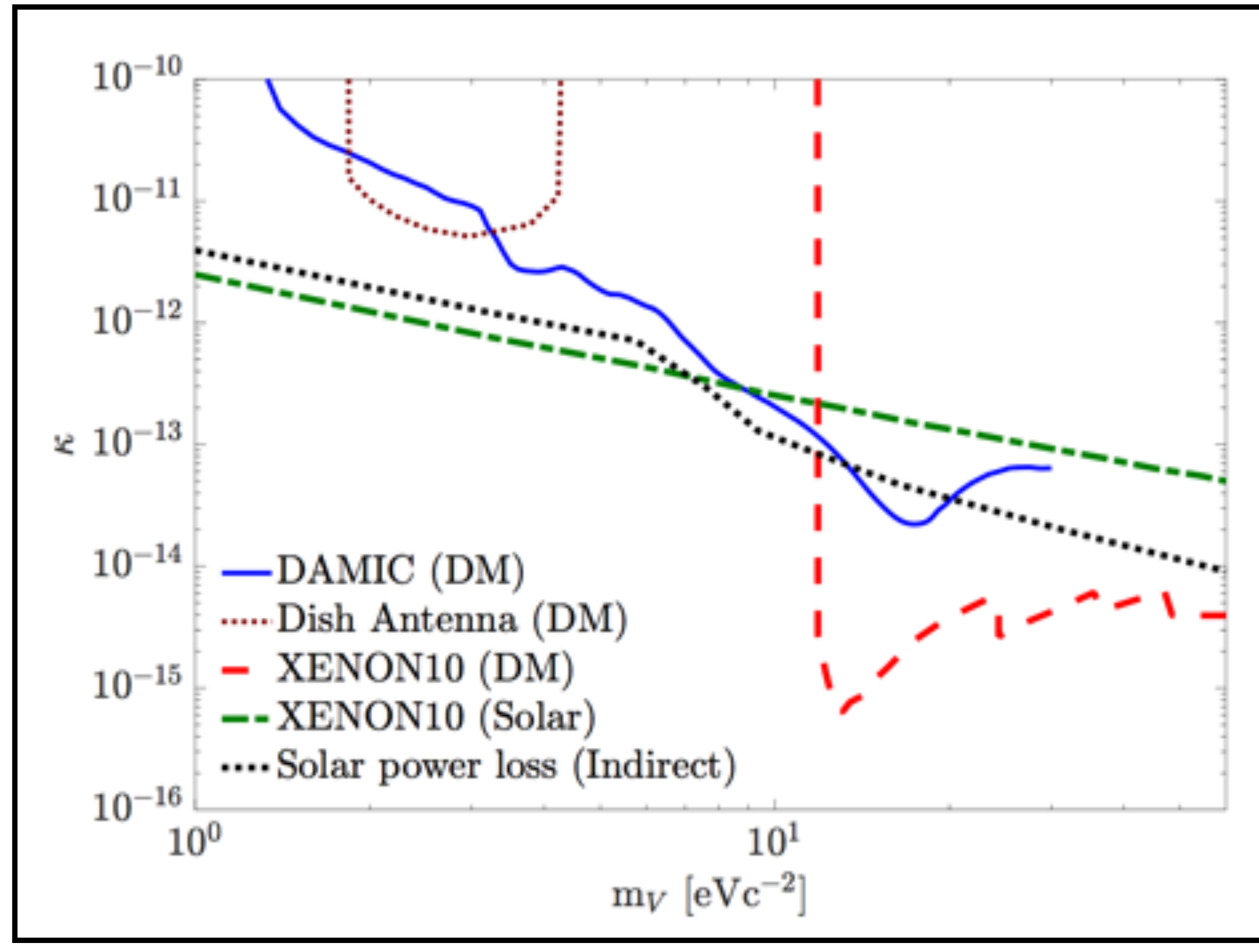
DAMIC result



Phys. Rev. D 94, 082006 (2016)

First direct detection constraints on eV-scale hidden-photon dark matter with DAMIC at SNOLAB



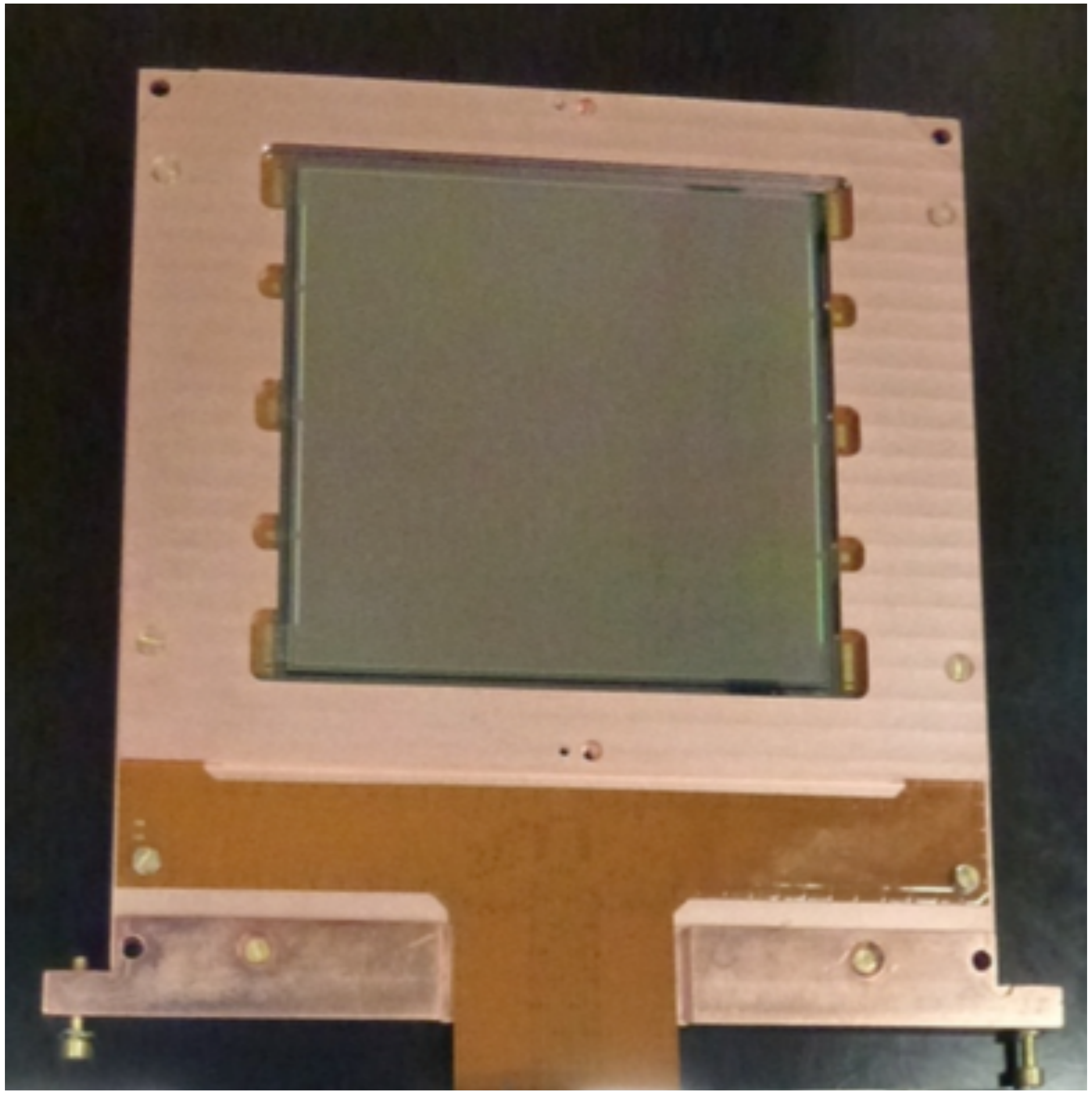


DC : 4e-/mm^2/day ~ 0.0009 e-/pix/day ~ 7x10^{-22} A/cm^2

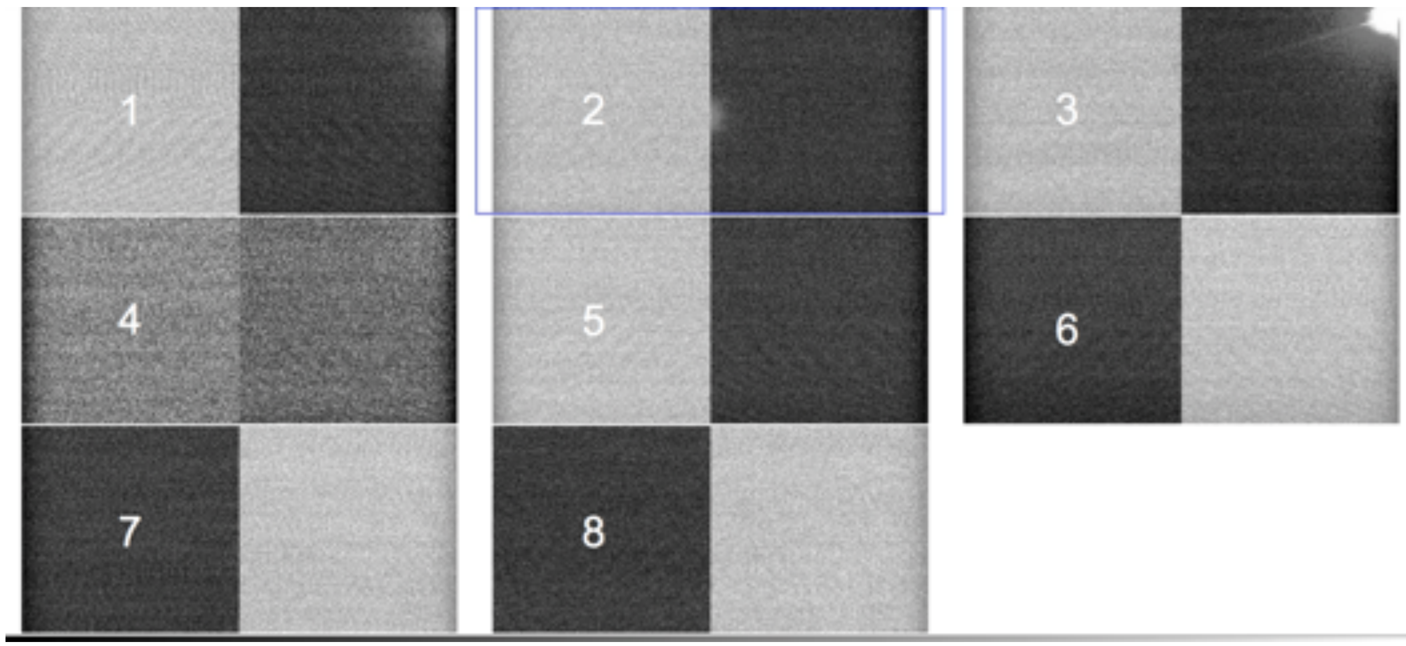
this dark current, by itself provides the best direct detection limits for low mass hidden-photon dark matter. We believe we have not reach the DC limit for the sensors yet.

arXiv:1611.03066

DAMIC-100 : now



8 detectors installed at SNOLAB in April-2016.

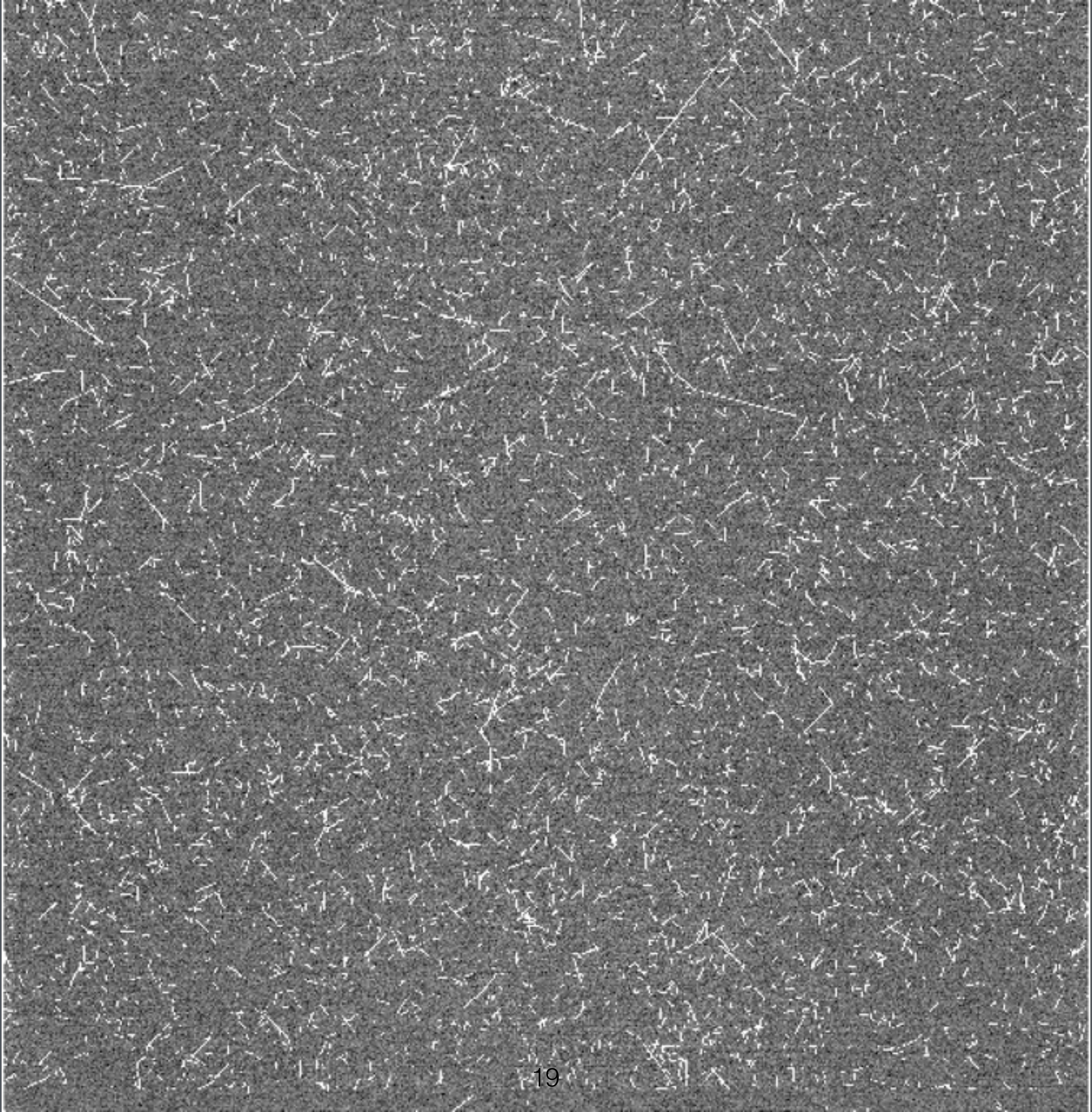


excess dark current seen in some sensors from mechanical stress. We have now made some changes to the procedures to eliminate this issue.

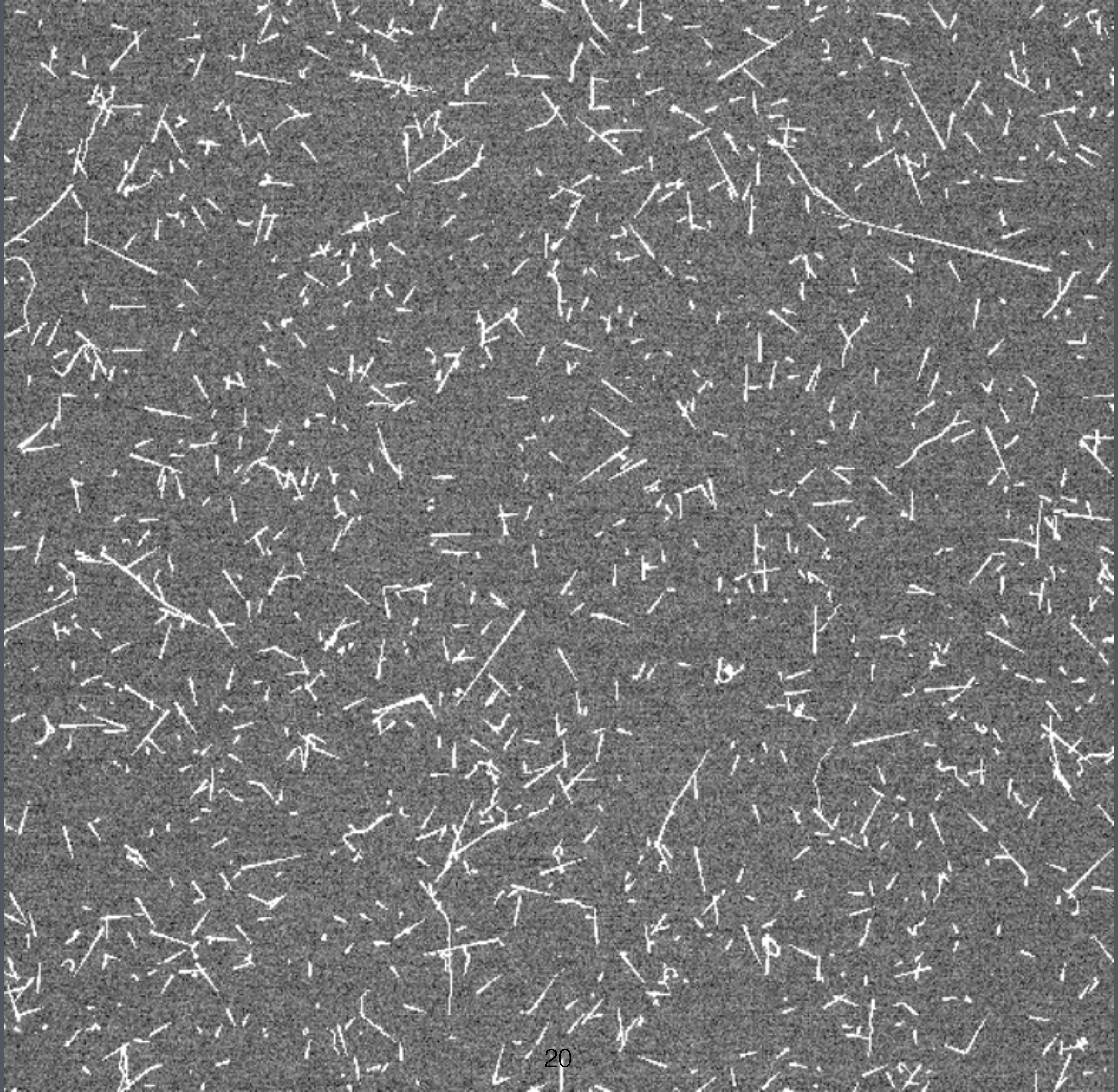
Science array currently being tested at FNAL, for installation at SNOLAB in January.

designed for 18 CCDs
16 Mpixels each
675 um thick
5.7 g/CCD
5 dru

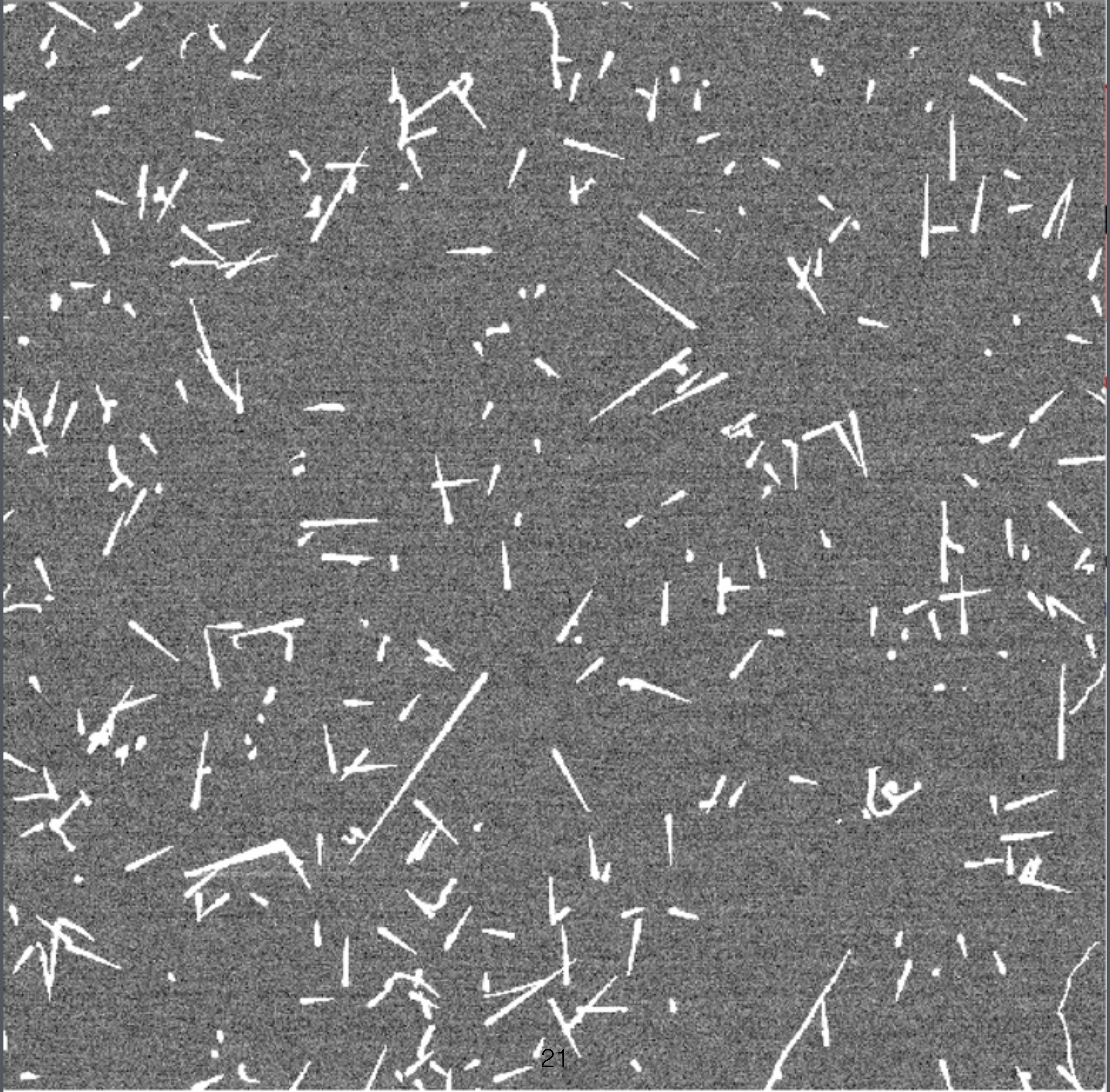
16 Mpix
3hr
surface



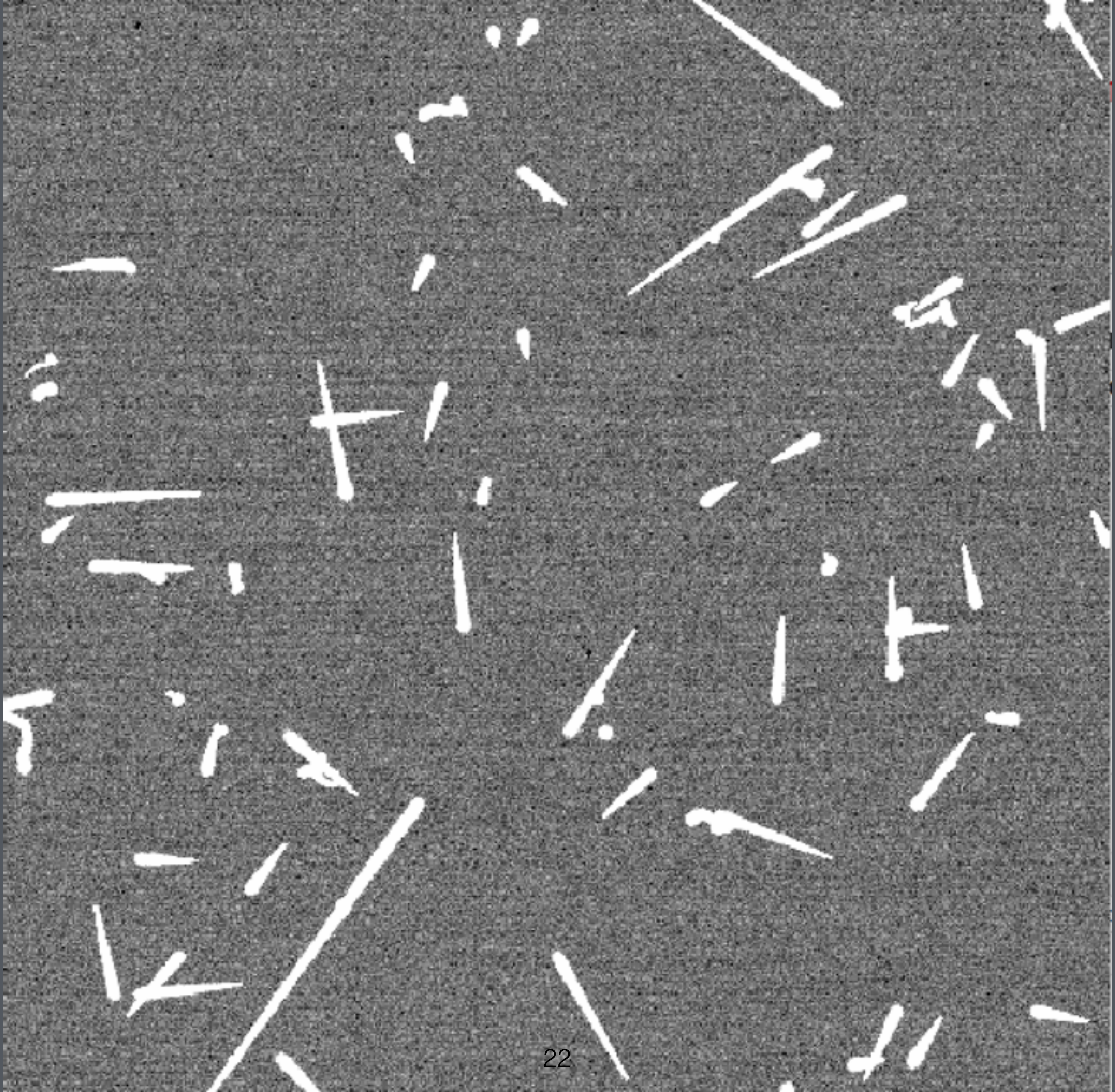
zoom



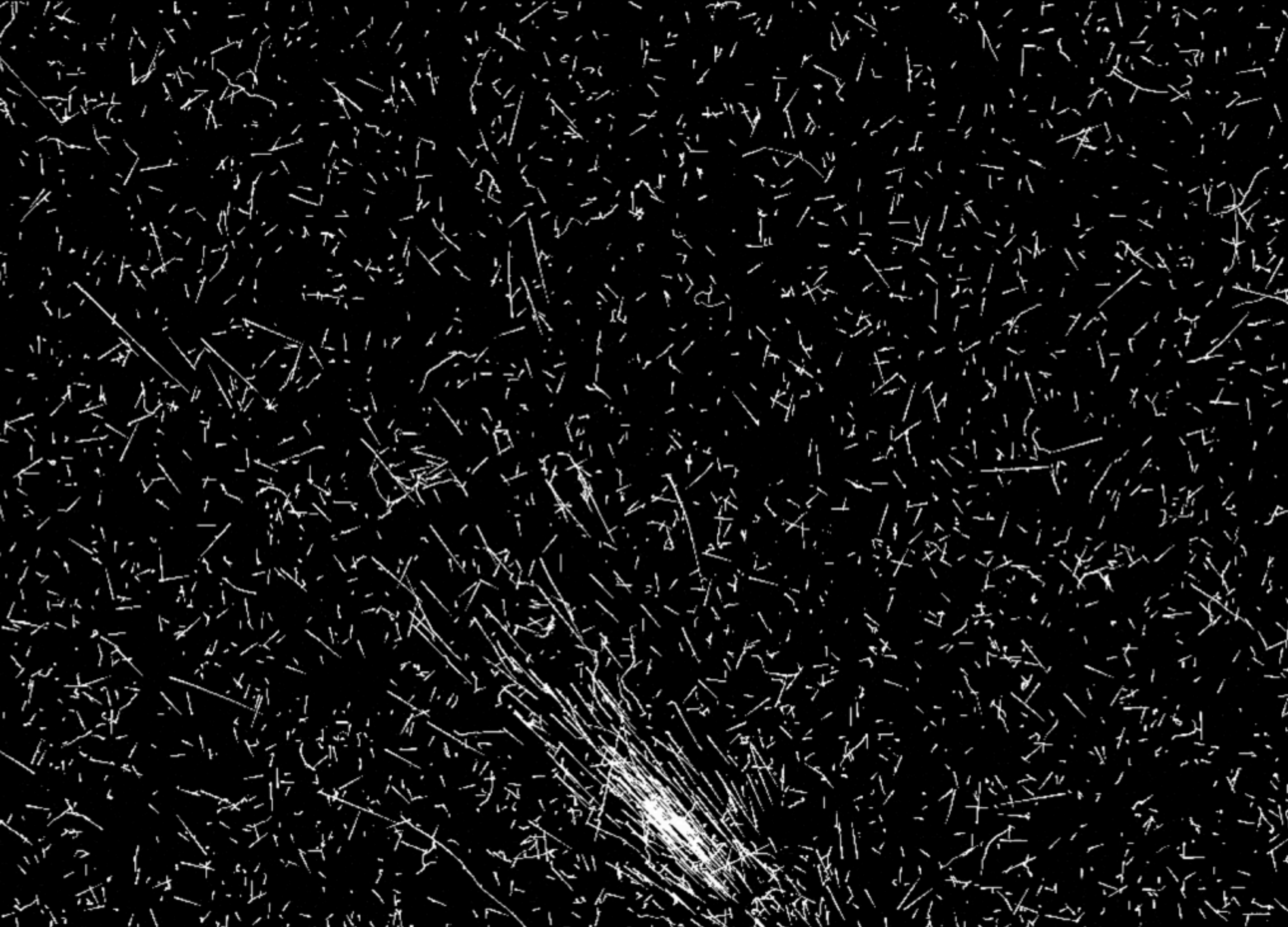
zoom2



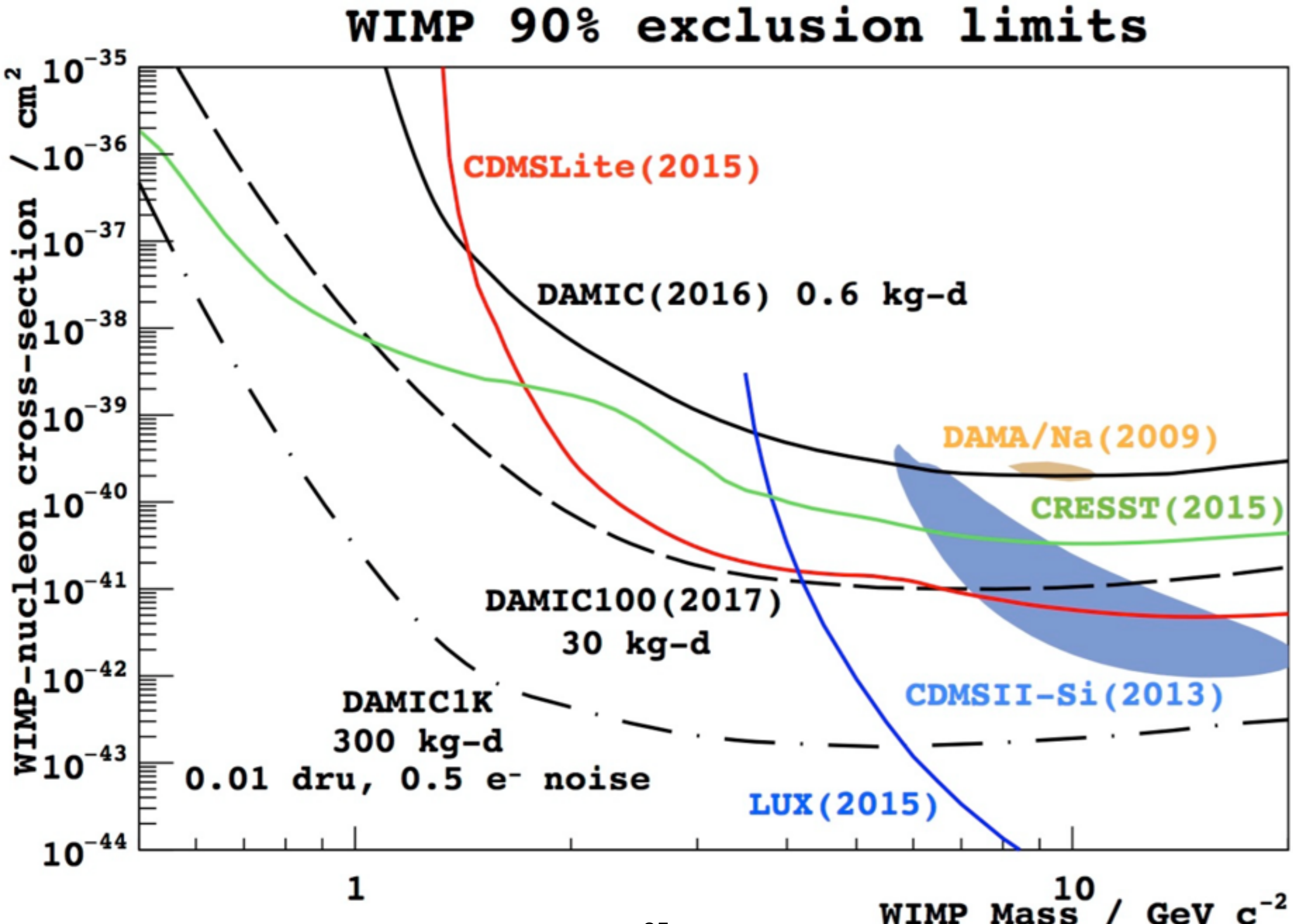
zoom3



Shower seen by 5 of these sensors in an array (tracking).



Next steps



WIMP 90% exclusion limits
WIMP-nucleon cross-section / cm^2
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
CDMSLite(2015)
DAMIC(2016) 0.6 kg-d
DAMA/Na(2009)
CRESST(2015)
DAMIC100(2017)
30 kg-d
CDMSII-Si(2013)
DAMIC1K
300 kg-d
0.01 dru, 0.5 e- noise
LUX(2015)
1
10
WIMP Mass / GeV c^{-2}

DAMIC-1kg

DAMIC1kg	DAMIC100
36 Mpix CCD, 1+ mm thick	16 Mpix CCD, 675 um thick
array of ~50 detectors	array of ~18 detectors
0.01 d.r.u	5 d.r.u
< 1. e- noise (RMS)	1.8 e- noise (RMS)

DAMIC-1kg

DAMIC1kg	R&D
36 Mpix CCD, 1+ mm thick	1 mm sensors is possible using the same production model we have now. **R&D effort at UChicago** to go thicker.
array of ~50 detectors	We need to think a bit about the mechanical design, cabling, cooling. This is not a very large concern, but need to do it efficiently to keep shield of a reasonable size and low background inside.
0.01 d.r.u	This is a **major challenge.** PNNL electro-formed copper is one of the critical components. **DAMIC100 to demonstrate that the radioactive contamination of the CCDs** is sufficiently low. **New package and shield.**
< 1. e- noise (RMS)	Also a big challenge, but **already achieved in the lab by LBNL** for some of the new detectors design. This will require a combination of **R&D on sensors and readout electronics.**

This scaling of the experiment will have to be matched by a scaling of the collaboration (not quite by the same factor), but we are bringing new groups with different expertise.

http://kicp-workshops.uchicago.edu/DAMIC1kg/

DAMIC

workshop

Towards a kg-size dark matter detector with CCDs

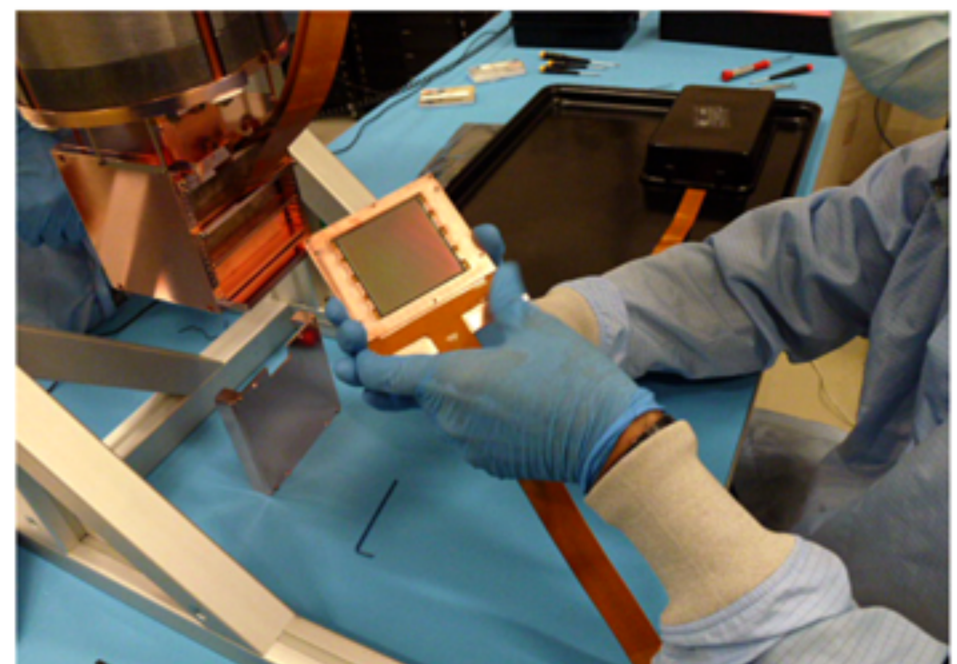
January 25-27, 2017 ● Chicago, IL

OVERVIEW | REGISTRATION | PARTICIPANTS | PROGRAM | PRESENTATIONS | LOGISTICS | KICP

Overview

On January 25-27, the Kavli Institute for Cosmological Physics (KICP) will be holding a workshop on "Towards a kg-size dark matter detector with CCDs." The workshop will gather a group of scientists interested in developing a kg-size detector based on the Charged-Coupled Devices technology.

The first day of the Workshop will be dedicated to review the current status and lessons learned with DAMIC100, a 100 g CCD detector installed at SNOLAB. The following days working groups will focus on specific topics (e.g. CCD development, Electronics, DAQ, Simulation and Data Analysis, etc.).



A DAMIC100 CCD with a 6 cm x 6 cm active area (16 Mpixels) and a record thickness of 675 µm.

Organizing Committee
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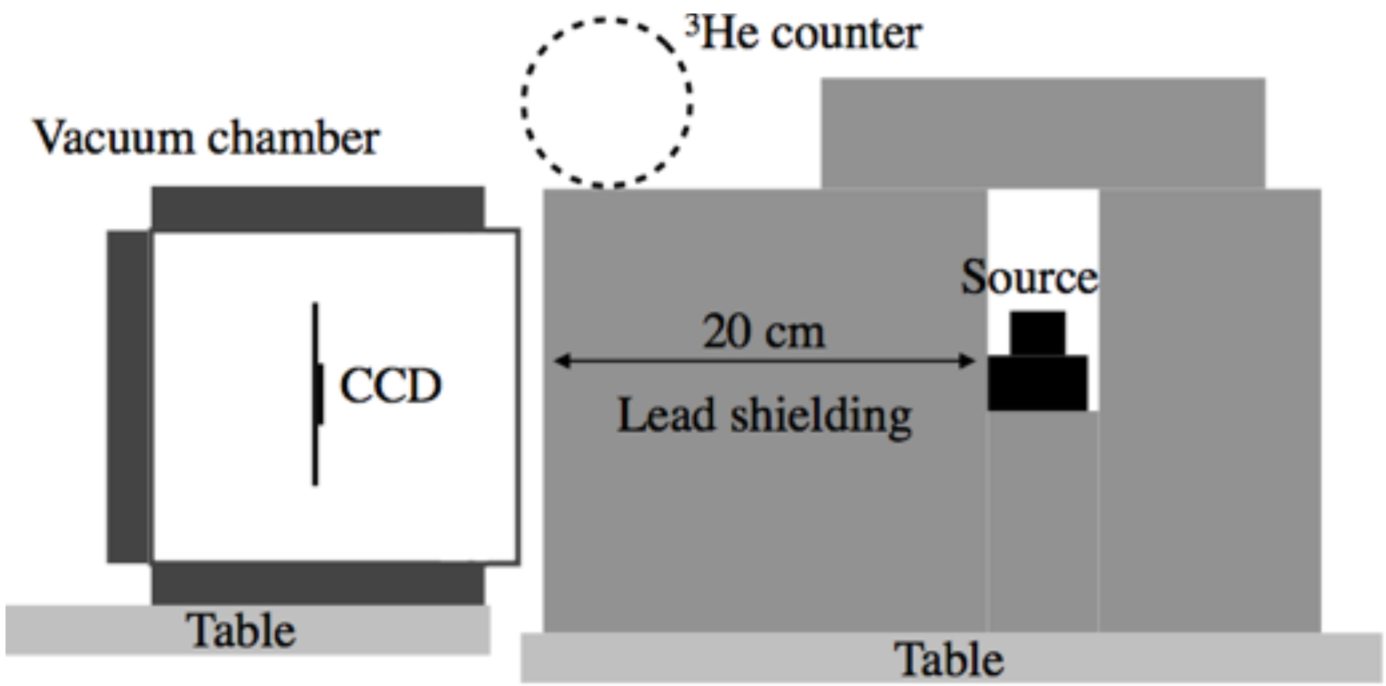
ORGANIZING COMMITTEE

Summary

- DAMIC results from 2015 produced the best limit for WIMP dark matter with silicon target.
- Detectors now calibrated for nuclear recoils down to threshold 0.7 keVr.
- First direct limit for dark photons using this technology published last month. More on this coming thanks to the impressive dark current of these sensors.
- Deployment of DAMIC-100 (with 5 d.r.u) planned for January.
- Getting ready for DAMIC-1kg.

arXiv:1608.00957



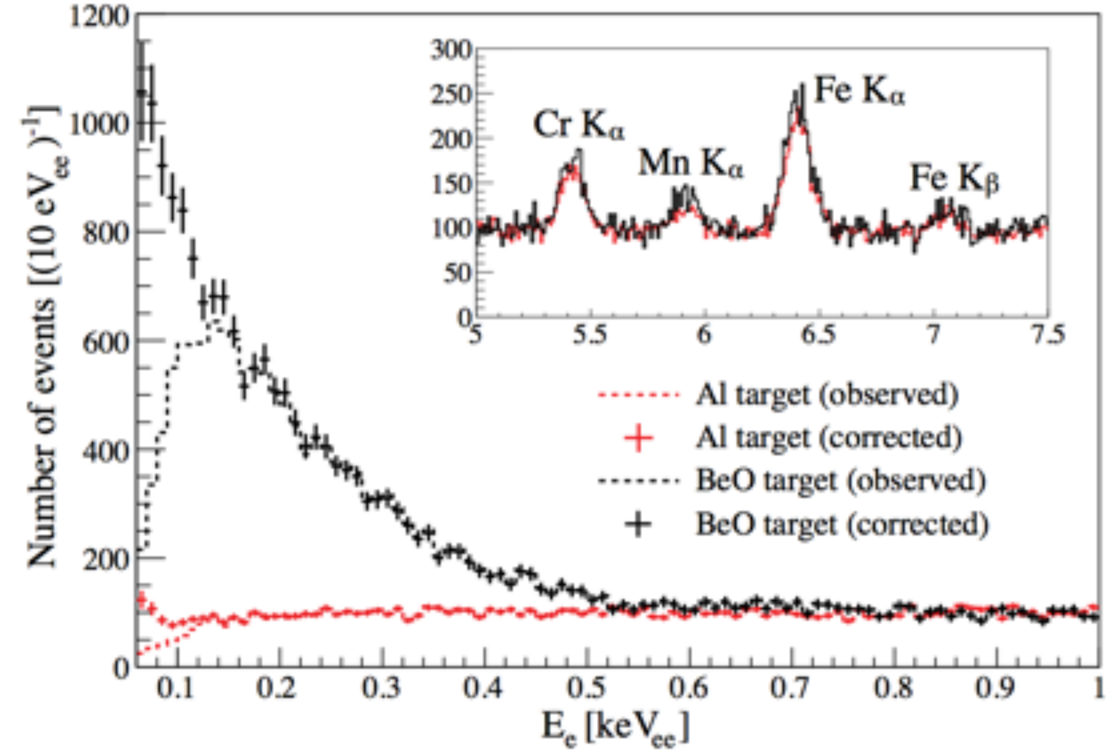


FIG. 2. Measured ionization spectra with the full BeO and Al targets (dashed lines). Solid markers represent the spectra corrected for the energy-dependent event selection acceptance. The inset shows the spectra in the 5.0–7.5 keV$_{ee}$ range, with in-run calibration lines from fluorescence x rays originating in the stainless steel of the vacuum chamber.

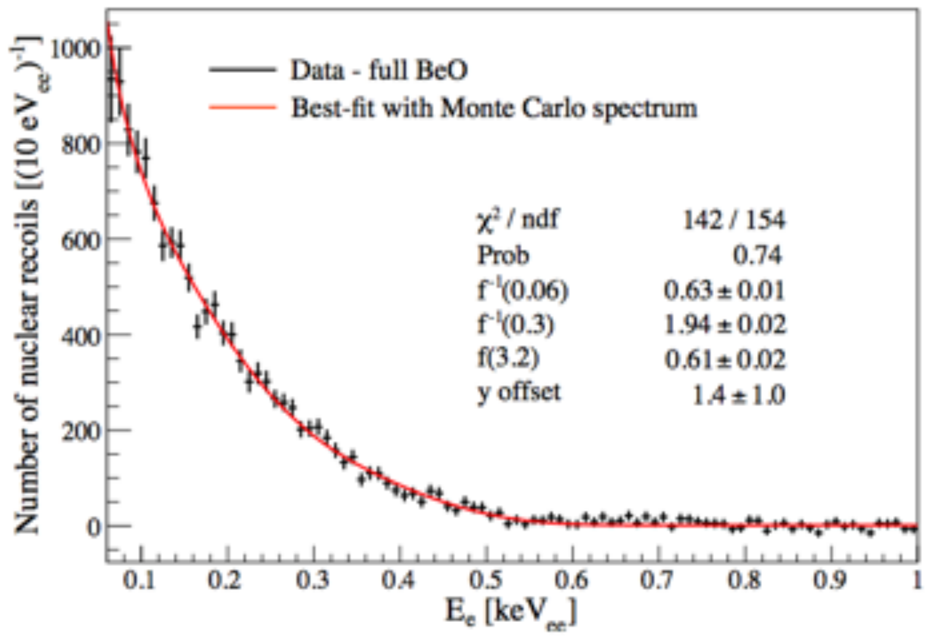
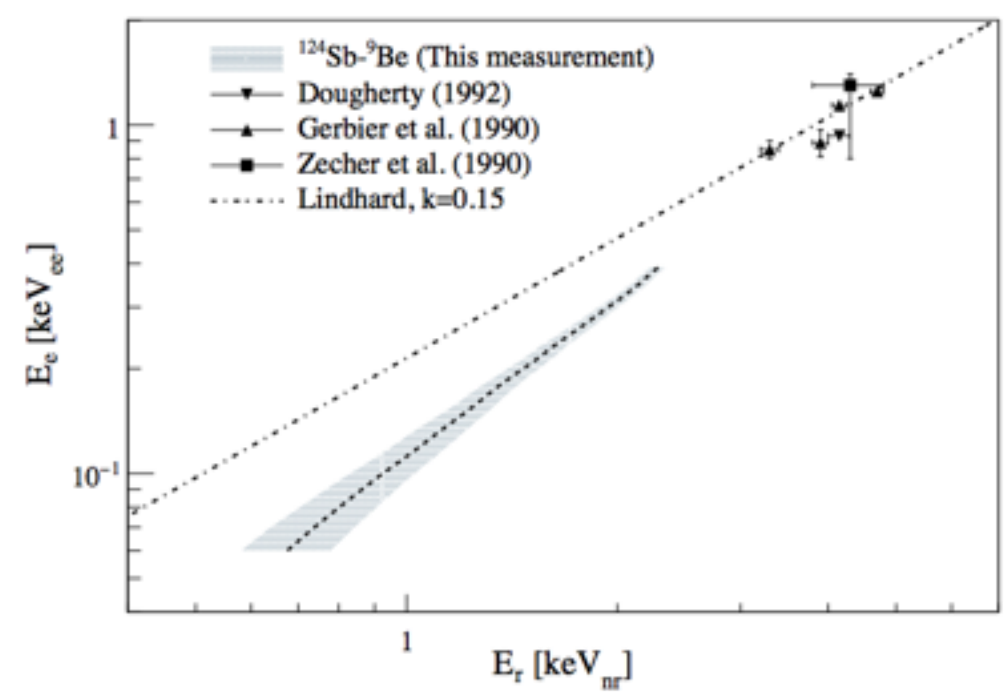


FIG. 4. Ionization spectrum of nuclear recoils induced by neutrons from the full BeO target source (black markers) and best fit to the data (solid line). The fitting function was obtained by applying a cubic spline model f of the nuclear recoil ionization efficiency to the simulated recoil spectrum and convolving with the detector energy resolution. The best-fit parameters of the spline are given in the legend.



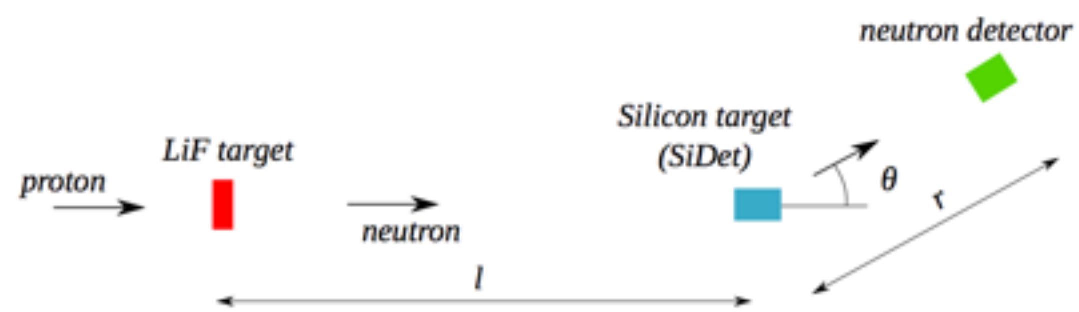
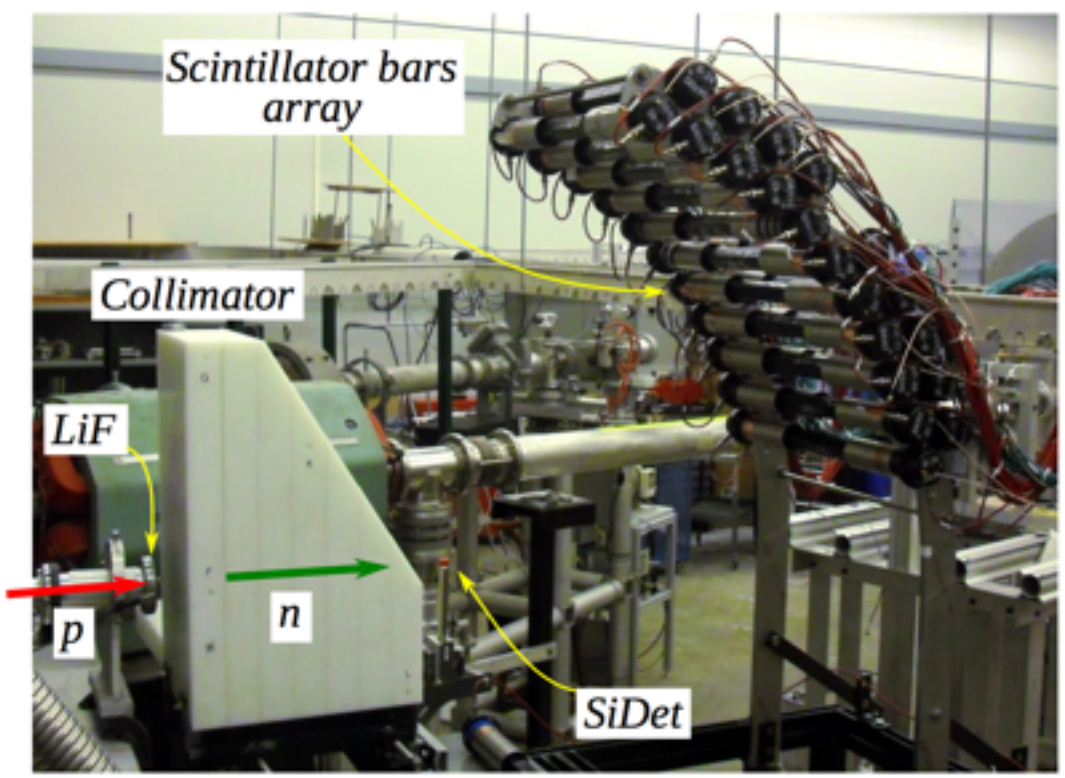
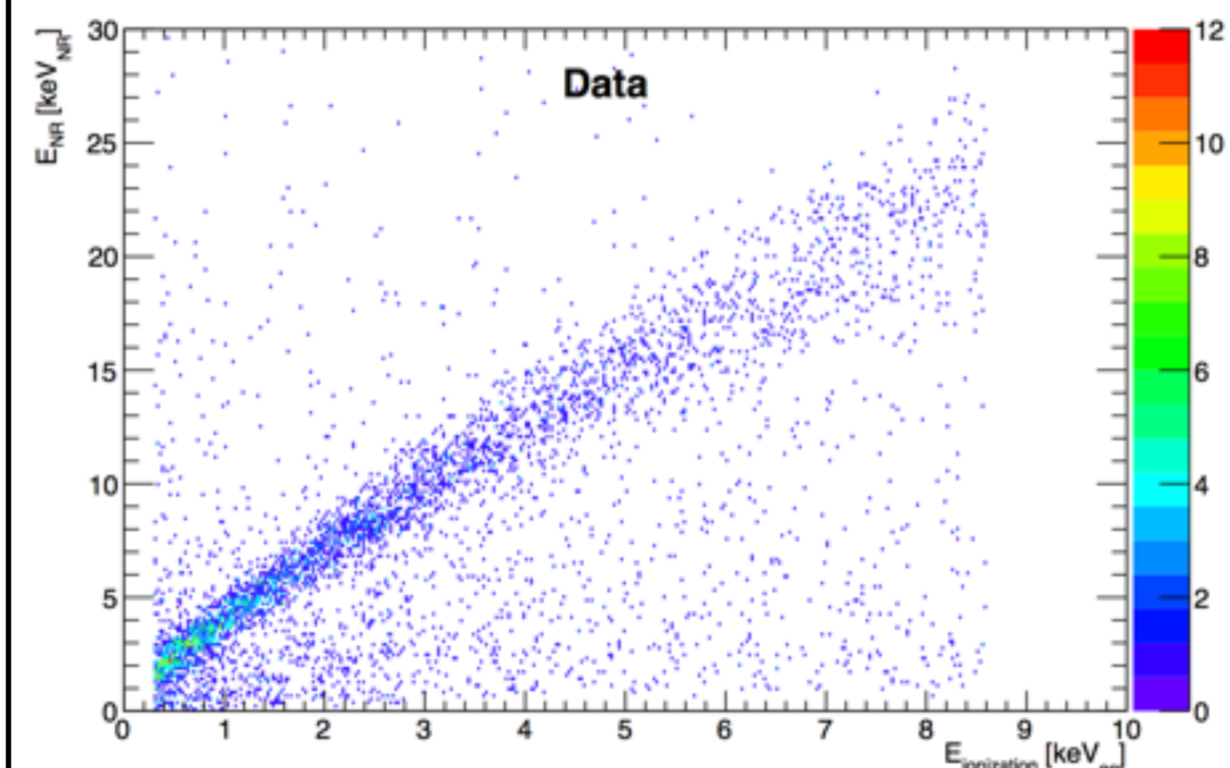


Figure 1: Schematic layout of the experimental arrangement.





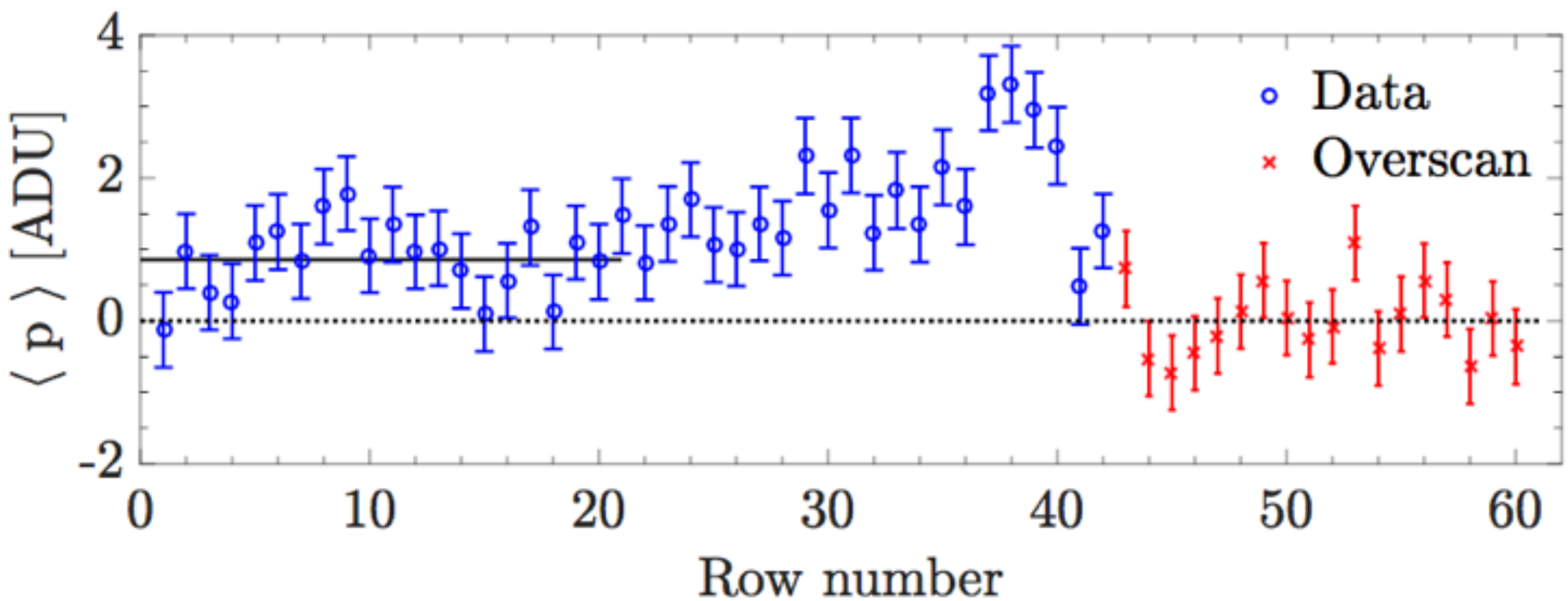
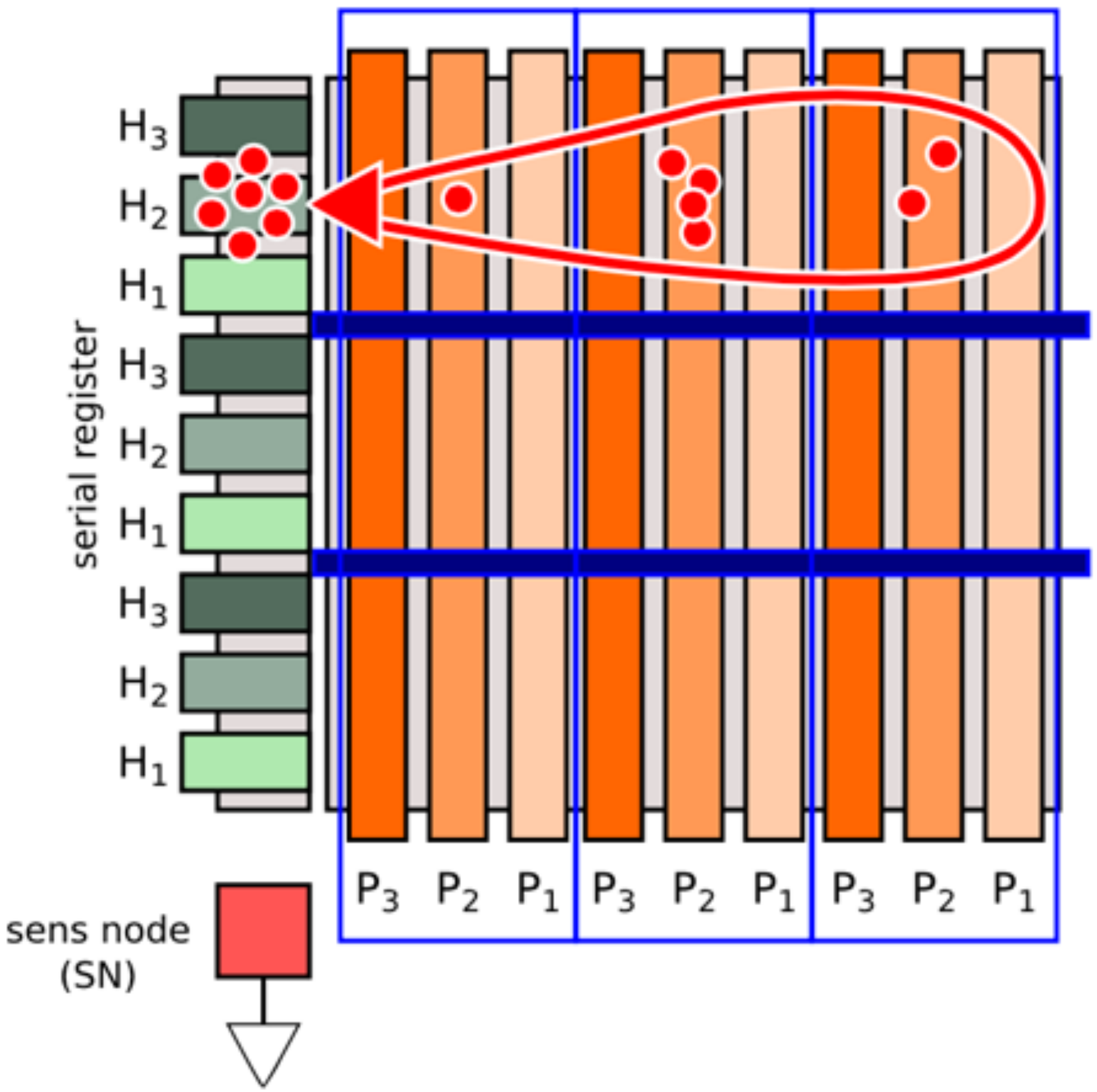


FIG. 1. Mean of the pixel values in each row over the nine images, $\langle p \rangle$, as a function of row number. The first 42 rows contain the CCD data, while the remaining 18 rows constitute the y overscan. The dotted line shows $\langle p \rangle$=0, while the solid line presents the level of leakage charge that corresponds to λ=4.0 e^{-} mm^{-2} d^{-1}.

0.695 d on each exposure



- Every readout introduces a $2e^-$ noise
- The CCD allows you to add charge in the sensor (binning) and then readout many pixels as a single one
- This improves signal to noise, effectively increasing the efficiency at low energy

$$\mathbf{S/Noise} = \frac{\mathbf{Q}}{\mathbf{N_{reads}}}\sigma$$

Reading the charge in less pixels is good!